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Report

Snake Robots for Space Applications (SAROS)

Author(s)
Mariann Merz
Aksel A. Transeth, Gorm Johansen, Magnus Bjerkeng

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SINTEF Digital
SINTEF Digital
Address:
Postboks 4760 Torgarden
NO-7465 Trondheim
NORWAY

Enterprise /VAT No:
NO 948 007 029 MVA

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ABSTRACT

This report explores relevant concepts for use of snake robots in Space, specifically for use onboard the International Space Station, for exploration of Moon lava tubes and for exploration of low-gravity bodies such as asteroids, comets and small moons. Key abilities that snake robots need to have in order to carry out the aforementioned operations, as well as challenges related to realizing such abilities are discussed.

PREPARED BY Mariann Merz	SIGNATURE
CHECKED BY Giancarlo Marafioti	SIGNATURE
APPROVED BY Sture Holmstrøm	SIGNATURE

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0.1	2016-06-11	Early-draft version as basis for discussions with ESA regarding concepts and scenarios.
1.0	2017-09-28	Final Report for delivery to customer
2.0	2018-03-01	Report updated with missing Acknowledgements.

Executive summary

The report considers the use of snake robots in space applications in the not too distant future. The key properties of snake robots in a space environment are considered, and are used to identify scenarios and concepts of interest where the snake robots may have advantages over other mobile space robots. The primary advantages of space-bound snake robots are:

1. The long and slender shape that provides **VERSATILITY**, specifically the ability to
    a. traverse rough and cluttered terrain;
    b. move across wide gaps/cracks in the terrain;
    c. access narrow passages;
    d. perform whole-body grasping;
    e. achieve motion through several locomotion strategies;
    f. maintain stability due to many support points and low centre of gravity;
    g. recover from major upsets, as there are no "upside down" problem.
2. The modular structure provides **ROBUSTNESS**, i.e. ability to
    a. maintain propulsion even if some joints fail;
    b. simplify production, testing, maintenance and logistics;
3. The snake robot is both a mobile robot as well as a manipulator arm.

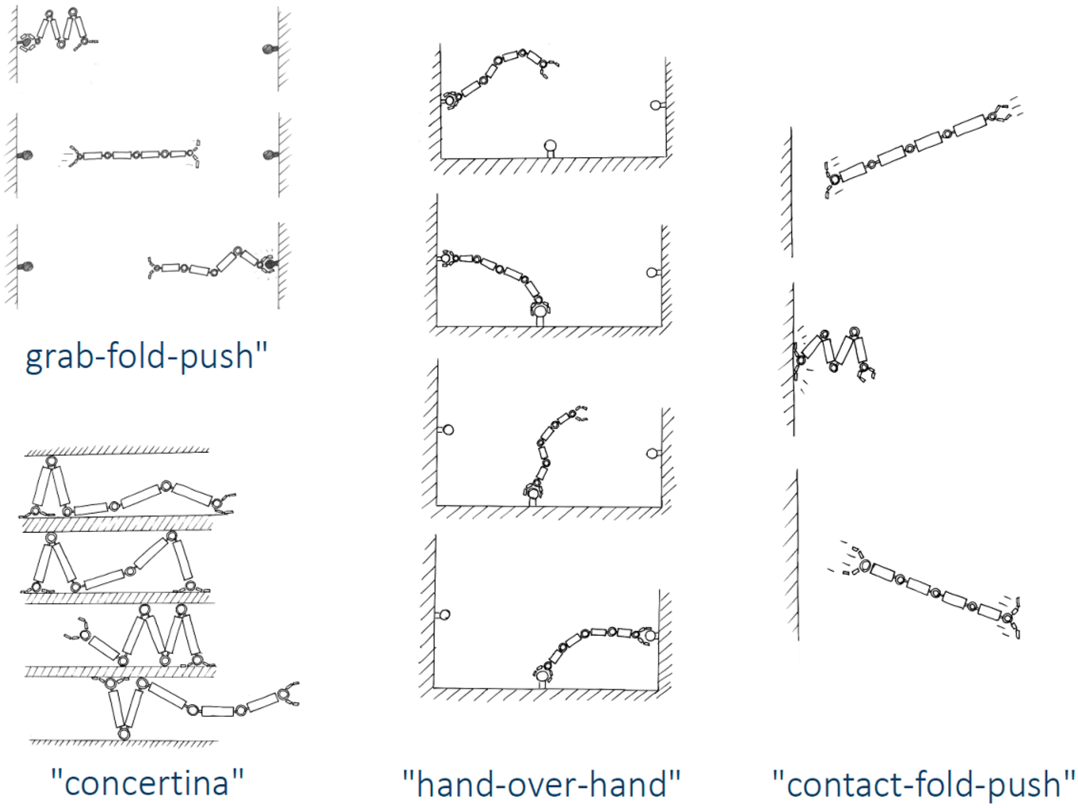
In addition, the snake robot solution involves some less desirable characteristics, and the key disadvantages are:

4. Low speed.
5. Limited payload due to slender shape.
6. Complex propulsion/control system due to many joints in modular structure.
7. Relatively low energy efficiency for surface mobility.

Considering the numbered list above and the competing technologies, three scenarios were identified as the most promising for near-term implementation. The three scenarios and the accompanying snake robot concepts are summarized next.

<u>Scenario/Concept 1: Snake robots to perform inspection and intervention tasks on-board the ISS</u>

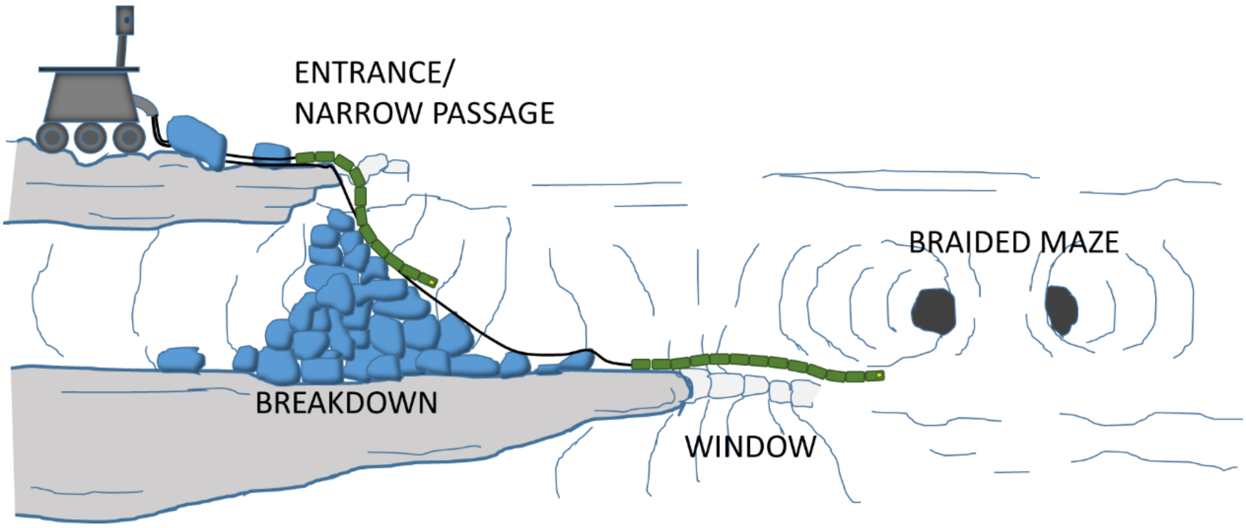
A key advantage of a (possibly autonomous) snake robot inside the ISS is its ability to access hard-to-reach spaces such as in between and behind infrastructure. By having the ability to grip handrails/features with both ends of its body, it could move around the low-gravity environment in an inchworm-like fashion as suggested in the figure on the next page. Active and passive mechanisms can be included in the snake robot design to protect the crew and ISS from harmful impact loads.



Snake robot locomotion candidates.

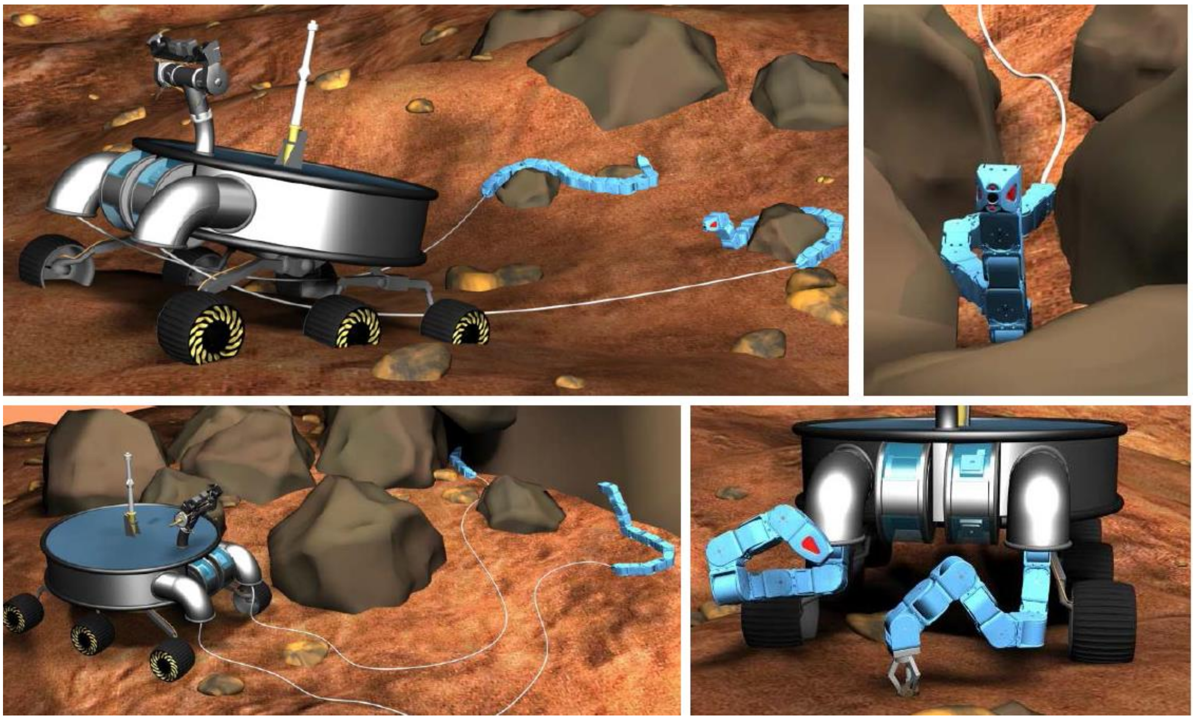
Scenario 2/Concept 2: Snake robots for planetary exploration, specifically to explore lunar lava tubes

A snake robot could be used for missions requiring planetary exploration in face of terrain that challenges wheeled/tracked robots. The figure below illustrates exploration of a lunar lava tube, showing how the snake robot characteristics may be relevant.



Snake robots exploring (lunar) lava tube with rover.

Collaboration with a wheeled rover will increase the reach of the snake robot and significantly increase data capabilities. While a tethered connection would be advantageous, untethered operations where the rover serves as a docking station may be another option. We expect a snake robot for planetary exploration to have a relatively high mass compared to snake robots used on earth, particularly due to the more demanding requirements for environment protection and heating. A major challenge is therefore to obtain sufficiently strong and light-weight motor-gear system to actuate the snake robot's joints with this aforementioned additional mass. This challenge is, of course, less of a concern – but still notable – on the Moon compared to on Mars.



Conceptual overview of a rover equipped with deployable snake robots and possible applications.

Scenario 3: Snake robots to explore low gravity bodies (asteroids, small moons, comets)

For low-gravity bodies, such as an asteroid, the main challenge is how the surroundings can be explored in a controlled manner when traction is virtually absent and the terrain and surface properties are likely not known. Obstacle-aided locomotion where the snake robot push against ground/surface irregularities are particularly relevant for this scenario. Furthermore, it may be helpful to add "caterpillar features" for additional gripping capability.

For most autonomous applications involving a snake robot in space, efficient locomotion planning such that the optional path considers mission surface characteristics, terrain profile, available locomotion types, system limitations and mission details will allow the technology to reach its full potential.

Another major challenge is the protection of delicate snake robot components against the harsh space environment. While well-proven technologies such as lightweight Solid Silica insulation and Radioisotope Heater Units will contribute towards this goal, emerging technologies such as Variable Emittance Coatings and pumped liquid cooling system for micro/nano spacecraft will be necessary to achieve the required protection.

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The report includes a list of key functions and a first iteration of relevant high level requirements for each fo these function. Finally, the core technologies are identified, and a maturity level (where 1 is *immature* and 3 is *mature*) for each of these have been assigned for each of the three candidate snake robot concepts (designated C1 through C3). A table summarizing this analysis is provided next.

Core technologies necessary to realize snake robot concepts.

Technology	Maturity Level			Comments
	C1	C2	C3	
SENSING AND PERCEPTION				
Proximity detection	2	2	2	Refer to discussion in Section 6.1.1.
Object pose estimation	2	-	-	Refer to discussion in Section 6.1.2. Considered core technology for ISS scenario only.
Robot absolute pose estimate	2	2	2	Refer to discussion in Section 6.1.3.
Contact sensing	2	2	2	Refer to discussion in Section 6.1.4.
Inherently safe joint movement	2	-	-	Core technology for ISS scenario only. Refer to discussion in Section 6.1.5.
Marker pose estimation	3	-	-	Core technology for ISS scenario only.
Item identification	3	-	-	Core technology for ISS scenario only.
MECHATRONICS				
Joint actuation	2	1	1	Refer to discussion in Section 6.2.1.
High Friction Contact	2	2	2	Refer to discussion in Section 6.2.2.
Collision absorption	2	-	-	Core technology for ISS scenario only. Refer to discussion in Section 6.2.3.
Anchor to the ISS	2	-	-	Core technology for ISS scenario only. Refer to discussion in Section 6.2.4.
Non-tethered: On-board energy generation	-	2	2	Core technology for exploration of Moon Lava tubes and low gravity bodies scenarios only. Refer to discussion in Section 6.2.5.
Environment protection	2	1	1	Refer to discussion in Section 6.2.6.
MOBILITY				
Path Planning	2	2	2	Refer to discussion in Section 6.3.1.
Locomotion Planning	1	1	1	Refer to discussion in Section 6.3.2.
Locomotion Types	1	1	1	Refer to discussion in Section 6.3.2.
Climbing	2	2	2	Refer to discussion in Section 6.3.3.

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List of abbreviations

Abbr.	Definition	Description
CPU	Central Processing Unit	
ESA	European Space Agency	
EVA	Extra-Vehicular Activity	Activities carried out outside space crafts or the ISS
HMI	Human-Machine Interface	
HRS	Heat Rejection System	System for thermal management
HVAC	Heating, Ventilation and Air Conditioning	
IR	Infrared Radiation	Electromagnetic radiation with wavelengths longer than that of visible light
IVA	Intra-Vehicular Activity	Activities carried out inside space crafts or the ISS
ISS	International Space Station	
LP	Locomotion Planner	
MBS	Mobile Base System	Along with Canadarm 2 it is part of the Mobile Servicing System on the outside of ISS
MEMS	Micro-Electro-Mechanical Systems	
MMRTG	Multi-Mission Radioisotope Thermoelectric Generator	A nuclear battery that reliably converts heat into electricity developed for NASA space missions
NTNU	Norwegian University of Science and Technology	
PDGF	Power Data Grapple Fixture	Handles on the outside of the ISS that the Canadarm2 use for locomotion.
PP	Path Planner	
RFID	Radio Frequency IDentification	RFID uses electromagnetic fields to automatically identify and track tags attached to objects
RHU	Radioisotope Heater Units	Small mall devices that provide heat through radioactive decay
SLAM	Simultaneous Localization And Mapping	
SPHERES	Synchronize Position Hold, Engage, Reorient, Experimental Satellites	Free-flying satellites onboard ISS
TBD	To Be Determined	
TEC	Thermo Electric Coolers	A solid-state active heat pump which uses electric energy to transfer heat from one side of the device to the other.
UWB	Ultra Wide Band	A radio technology
WEB	Warm Electronic Box	

1 Introduction

This section provides a brief description of the motivation and scope of this report as well as a presentation of the research team behind it.

1.1 Project Motivation and Contribution

Snake robots are long and flexible robotic mechanisms that can move like biological snakes and/or be operated as a robotic arm. An advantage of such mechanisms is their ability to move and operate robustly in challenging environments where human presence is unwanted or impossible. Moreover, snake robots can operate side-by-side with humans and contribute in a wide range of operations including those that require access to narrow and hard-to-reach areas. Applications of snake robot mechanisms include search and rescue operations in earthquake areas, inspection and maintenance in industrial process plants, and subsea operations.

In this report, we investigate concepts for snake robots for space applications – both for planetary exploration and for inspection and intervention operations on the International Space Station (ISS). Snake robots appear promising for space applications as they have great potential to be constructed such that they are compact and reasonably light weight. They can also incorporate a modular design that provides robustness by allowing one or several modules to fail while still executing the mission. Finally, snake robots can exploit a number of different locomotion/propulsion options to yield a very versatile mobile platform. Compactness, robustness and adaptability are key drivers for space mission equipment.

Based on the concepts deemed most relevant for a snake robot system, we identify suitable high-level functional requirements. Moreover, we will identify core technologies that are necessary to realize the functional requirements, and investigate the maturity of these. We also provide an introduction to snake robotics and discuss some advantages and disadvantages of snake robots.

For spin-off possibilities and synergies with earth-bound applications related to snake robots, please refer to [1].

1.2 The Scope of this Report

This report has the following objectives:

1) Define concepts for snake robots for space applications.
2) Outline functional requirements for one or more of the defined concepts.
3) Identify core technologies and potential for realization based on the identified requirements.

The focus of this report is operations at the ISS, exploration of lunar lava tubes and exploration of low-gravity bodies. Aspects such as detailed designs, as well as experiments and detailed quantitative analyses are outside the scope of this report. The report was written during the period May 2016– September 2017.

1.3 The Research Team behind this Report

This report is written by researchers at the Norwegian research institute SINTEF. SINTEF is the largest independent research organisation in Scandinavia with 2000 employees from 70 different countries. Fifty-five per cent of SINTEF researchers have a PhD-degree. SINTEF creates value and innovation through knowledge generation and development of technological solutions that are brought into practical use.

SINTEF has in cooperation with the Norwegian University of Science and Technology (NTNU) acquired an internationally leading position in modelling, control and development of snake robots, particularly targeting research challenges imposed by snake locomotion in irregular environments.

SINTEF initiated the first snake robot project in Norway in 2003 after several major city fires in Trondheim. An effort was made to bring the fire department in closer contact with the research community in Trondheim to stimulate efforts to improve fire safety. A specific idea that spurred from this initiative was the vision of a self-propelled fire hose as a robotic tool to aid human firefighters. This idea is clever in that the highpressure water inside the hose can be employed as a hydraulic medium in the propulsion mechanism, a fire extinguishing medium, and a cooling medium for cooling the robot in environments with extreme temperatures. The resulting system would be a robotic fire hose that could move in extreme environments with the agility of a biological snake, or, in other words, a water hydraulic snake robot. The Applied Cybernetics department at SINTEF was brought in to investigate this idea further, and so began the research activity on snake robots at SINTEF and NTNU. The research activities at SINTEF and NTNU related to snake robotics have resulted in:

- Publication of several papers in internationally recognized journals.
- Publication of a book (published by Springer), which is a complete treatment of snake robotics.
- The development of several snake robot prototypes, such as the fire-fighting snake robot Anna Konda (see Figure 1), which has attracted much national and international attention, and the snake robot Kulko, which is the first snake robot that can measure the magnitude of contact forces acting along its body.
- Close relations with key research communities working with snake robotics in Asia and USA.
- Several PhD-candidates and two PostDocs on snake robotics.
- The development of a robotic lab facility funded by a Norwegian oil and gas company.
- Eelume – a start-up company specializing in subsea inspection and maintenance with snake robots.

Researchers at SINTEF see great potential in the use of snake robots for space missions involving planetary exploration. The long-term motivation behind this project proposal is the development of robotic propulsion mechanisms, i.e., snake robots, which can reach and operate in locations not accessible by existing planetary rovers, as well as to support operations at the ISS.

Figure 1: Anna Konda - a water hydraulic snake robot - for many years the world's largests snake robot [2].

1.4 Acknowledgements

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2 Snake Robots – an Overview

This section provides a brief overview of the snake robotics platform, including the key advantages and disadvantages.

2.1 What is a Snake Robot?

Simply put, a snake robot is a robotic mechanism that is constructed to resemble and adopt the capabilities of biological snakes. They come in a variety of shapes and sizes depending on the application of interest, and they present a promising alternative for operating in environments where the mobility of wheeled and tracked robots are challenged. The long, thin shape is obviously well suited for the traversal and/or exploration of narrow spaces such as pipelines or tunnels. Moreover, the high degree of flexibility offered by the multiple joints allows the snake robot to scale objects and climb over various obstructions.

2.2 Advantages and Disadvantages of Snake Robots

The two main advantages of snake robots that results directly from the architecture are its properties of versatility and robustness. First, the snake robot is versatile as a single robot entity is able to

- traverse narrow passages *and*
- move over wide gaps *and*
- perform complex and light-to-medium-load manipulation operations.

The two first capabilities are illustrated in Figure 2, where a cooperative rover-snake robot system explores a (lunar) lava cave. The rover transports the snake robot(s) as close as possible to the narrow cave-entrance (or other challenging terrain that is inaccessible to the rover), and then deploys the snake robots for exploration of the cave/challenging terrain.

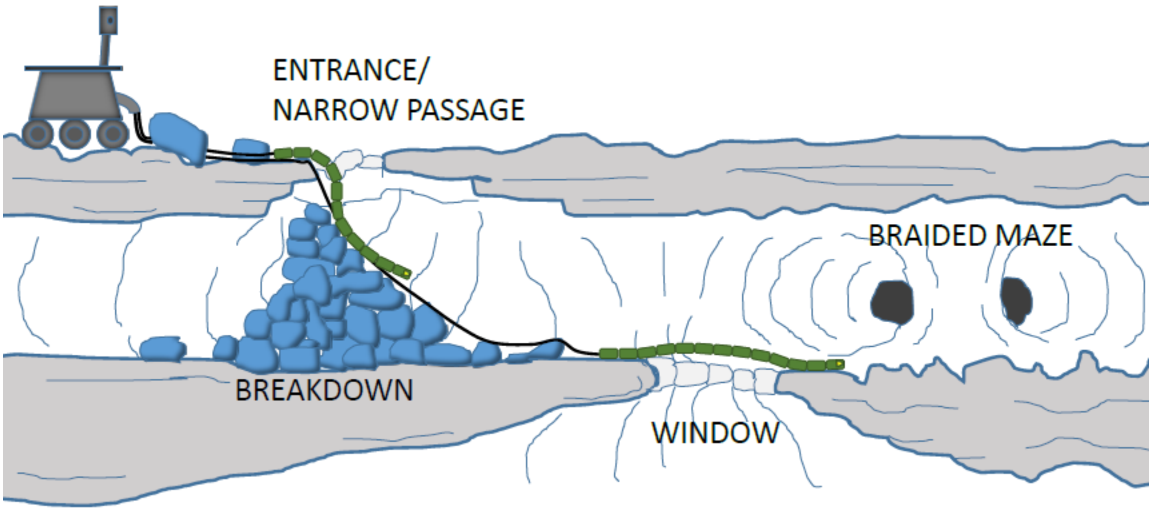

Figure 2: Snake robots exploring (lunar) lava tube with rover.

For other types of mobile robot mechanisms, there usually has to be a trade-off to favor either one or two of the listed capabilities. For example, a conventional mobile robot would have to be very small to traverse narrow passages, and small robots have very limited manipulation capabilities and will have difficulty moving over gaps in the terrain. This is not the case for snake robots as they constitute a mechanism, which is both a mobility device and a manipulation device at the same time.

Finally, the snake robot can be designed in a modular fashion allowing a robust design where the robot can perform the intended function even if some modules have failed. Additional benefits of a modular design include simplified production, testing, logistics (concerning spare parts) and maintenance assuming that the robot is built from identical modules.

In Table 1 and Table 2 we summarize all the key advantages and disadvantages of a snake robot design. Additional discussion is provided in the description of candidate scenarios in Section 4 and in the presentation of core technologies in Section 6.

Table 1: The main advantages tied to snake robot abilities in a space environment.

Main advantages of snake robots	Space mission context
Ability to traverse rough and difficult/cluttered terrain	Planetary exploration may offer rocky and cluttered terrain that need to be traversed. Biological snakes offer excellent traversability, and this is attempted recreated in snake robots in order to traverse, e.g., terrains on Mars. Such traversability can be utilized in order to carry missions into challenging terrain, for example geological and exobiological investigations through sample taking.
Ability to move across wide gaps in the terrain	The long narrow body is well suited to move over big cracks or gaps in the terrain.
Ability to access narrow passages and/or passage through small holes and gaps	Due to its small cross-sectional area, a snake robot may access narrow passages and enter areas that may not be accessible to other types of explorers. This can be beneficial with respect to, e.g., traversing rocky terrains (the snake robot could potentially slither in between the rocks), and for exploring small tunnels in connection with subsurface caverns. Moreover, even if the robot is small enough to enter narrow passages it can still carry out medium-load manipulation tasks. Hence, small "single-link" robots may match the ability to enter narrow passages, but not at the same time carry out medium-load manipulation tasks.
Ability to combine mobility and manipulation	A snake robot can function both as a mobile robot, as well as a manipulator arm which is an attractive feature for a variety of robot assisted human exploration missions. *Example 1*: A snake robot can attach itself to a rover and be utilized as a manipulator arm, or it can be deployed from the rover in order to investigate areas not accessible to the rover. *Example 2*: A snake robot moves around inside the ISS and performs inspection/manipulation operations where necessary.
Ability to do "whole body grasping"	A snake robot can be fitted with a gripper as an end-effector, but it can also employ parts of its body as a gripping tool by "enveloping" around the object to be grasped. This can for instance be used to anchor one end of the snake robot while the other end performs an intervention operation. Or it can be used to provide a more stable grasp of a free-floating body (i.e., ensure that the object does not float away) compared to what would be possible with a conventional robotic gripper.

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Stability: The long body of a snake robot provides many distributed support points, as well as that it has a low centre of gravity.	Snake robots may provide a stable mobile system for locomotion in rough and steep terrains such as craters and caves.
Recoverability: For most practical purposes, there is no "upside down" problem for snake robots.	A snake robot may roll down a hill or lose balance (and fall on its "back") while traversing a rock without this having any consequence for further locomotion capability. This is because snake robots in general work just as well "upside down".
Redundancy: Propulsion may be maintained even if some joints fail.	For unmanned planetary exploration missions, there are few if any possibilities of maintenance if something goes wrong with a robot system. Snake robots can possibly achieve mobility even if one or more of the robot joints fails. For such scenarios, the energy-efficiency of the robot system will most likely be reduced.
Combination of propulsion mechanisms	A snake robot can combine several propulsion mechanisms. For instance, a snake robot for surface/subsurface mobility can combine tracked-propulsion with a slithering locomotion similar to biological snakes, and a snake robot outside the ISS could combine thruster-based propulsion with pushing and pulling on the ISS to move between locations.

Table 2: Main disadvantages of snake robots in a space environment.

Main disadvantages of snake robots	Space mission context
Low speed	Snake robots are expected to achieve lower speeds than wheeled or tracked robots in terrains with a somewhat hard and reasonably flat surface. On softer terrains wheeled mechanism may get stuck, and legged mechanisms or snake robots could possibly achieve higher speeds. A rover can be used to transport snake robots for larger distances in order to deploy the snake robots close to, e.g., entrances to grottos or other terrains that the rover is unable to access. With this approach, the low speed of the robot is less critical.
Limited payload	Snake robots should be employed for "small-scale" mission (e.g., soil sampling) rather than missions which require bigger/heavier payloads. Such payloads could instead be carried by an accompanying rover.
Complex propulsion system	A large number of robot joint mechanisms are required in order to achieve locomotion with snake robots. This lead to a rather complex propulsion system. On the up-side, a snake robot can be designed to be modular with a large degree of similarity between the different snake robot modules. This in turn simplifies the robot design and manufacturing processes.

Relatively low energy efficiency for surface mobility	Snake robots should be tethered and connected to a larger rover for power supply. The long and slim body constitute a non-ideal structure for incorporating both a separate power source and the accompanying hardware necessary for planetary missions. A tether imposes a challenge given that it can get stuck, but the tether can also possibly be utilized in order to pull the rover free if it has gotten stuck. See [1] for further discussions regarding tether usage.

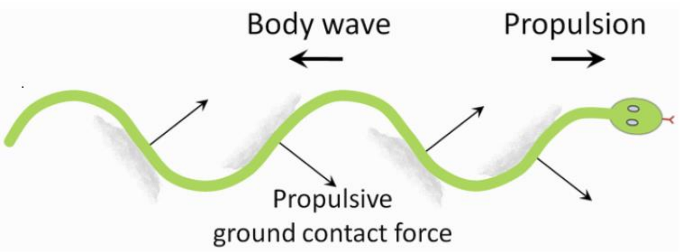
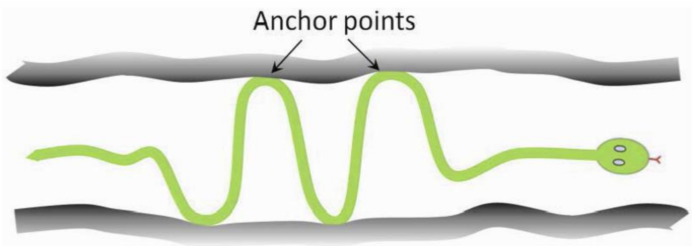
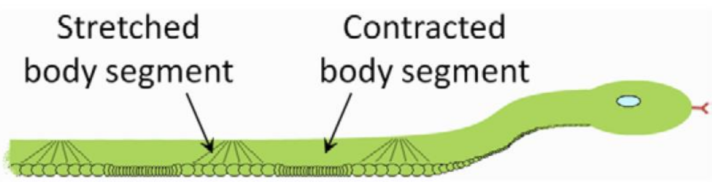
2.3 Special Considerations for Snake Robots in Space

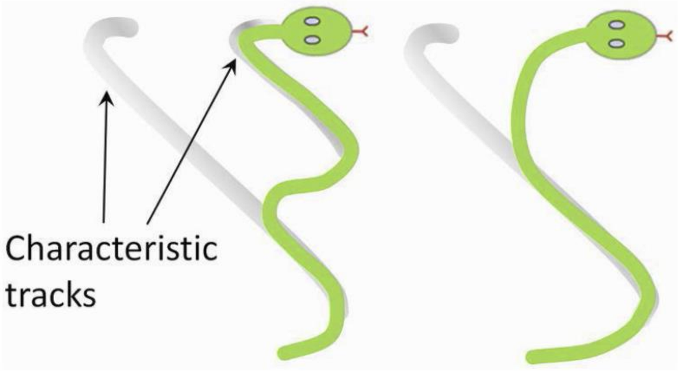
As with any space bound equipment a key consideration for a snake robot for operation in a space environment is weight and robustness. Hence, for construction of the snake robot, lessons learned from the construction and duration of previous space hardware need to be reviewed carefully. For missions involving planetary exploration, the experience gathered from the Mars Exploration program will provide insight into the material selection process. The materials need to be light weight and also hold up over extended time in an extremely harsh environment.

2.4 Modes of Locomotion for a Snake Robot

The four most common types of biological snake locomotion are described in [1] and are also summarized in Table 3 for convenience.

Table 3: Overview of key snake locomotion types.

Snake Locomotion Type	Description of Motion
LATERAL UNDULATION 	• Fastest and most common snake locomotion. • The sides of the snake push against surface irregularities, thus pushing the snake forward. • Not effective on flat, slippery surfaces.
CONCERTINA LOCOMOTION 	• Best suited locomotion to traverse narrow spaces. • The body curves to provide anchors against the environment allowing the snake to push the body forward. • This type of motion is energy inefficient, so only to be used when necessary.
RECTILINEAR CRAWLING 	• Slow form of locomotion often employed by heavy snakes or in final stages of stalking their prey. • The snake uses the edges of the scales on its underside as anchor points to pull itself forward. • Alternate parts on the snake will be stretching and pulling at the same time.

SIDEWINDING	
	• Employed by certain snakes to move across loose or slippery substrates, such as loose sand or mud. • The head is thrown sideways while the rear part of the body provides the anchor to the ground. Then the body follows while the head is anchored and then the motion repeats.

3 Candidate Scenarios for Snake Robots in Space Applications

As previously described in [3] there exists a large number of tasks that an articulated robot could perform in space. Examples include manipulating out-of-reach or hard to access objects as part of equipment servicing, explore otherwise inaccessible areas (remote planets/asteroids or constrained spaces) or relieve humans from mundane inspection work. In this section, we explore scenarios involving the use of snake robots in space applications. A **scenario** is an example of a snake robot concept being taken into use. E.g., an astronaut could possibly use the aforementioned snake robot arm as an extension to the astronaut's arm in order to get access to hard-to-reach areas on the ISS.

The following three scenarios were considered the most promising for successful implementation in the not too distant future:

- Scenario 1: Snake robots to perform inspection and intervention tasks on-board the ISS, such as to inspect the hard-too-see spaces behind the equipment racks.
- Scenario 2: Snake robots for planetary exploration, specifically to explore "lava tubes" on the Moon to determine if they are suited to use as enclosures for a permanently inhabited base.
- Scenario 3: Snake robots to explore low gravity bodies such as asteroids.

Also, as part of the selection process, the following additional scenarios have been suggested and considered:

- Scenario 4: A snake robot to behave as an astronaut's extended arm.
- Scenario 5: Snake robots used for logistics operations.
- Scenario 6: Snake robots to perform inspection and manipulation of infrastructure in space (other than the ISS). E.g., satellites and other future space assets.

Other possible usages relevant for planetary exploration that were discussed:

- Scenario 7: Below-surface mobility. Snake robots can slither through granular and liquid media, or drill down through ice and swim around in liquid possibly found on other planets/moons.
- Scenario 8: The snake robot could act as a manipulator arm with e.g., a gripper tool or an extra camera for the rover.

For completeness, a brief discussion of the first six scenarios have been included below even though a full snake robot concept will be developed only for the first three (in Section 4).

3.1 Scenario 1: A Snake Robot for Inspections and Interventions Onboard the ISS

A snake robot could move around inside the ISS either completely autonomously or with some astronaut assistance/supervision and perform inspection and intervention operations. Competitive robotic systems with the potential to fulfil similar tasks onboard the ISS includes:

- SPHERES – consists of 3 free-flying bowling-ball-sized spherical satellites that are used to test a diverse range of science hardware and software, typically related to docking maneuvers, formation flight or other autonomy algorithms. System due to be phased out at the end of 2017.
- Astrobee – new free-flying robot system for performing Intravehicular Activity (IVA) onboard the ISS that builds on the SPHERES technology, but also includes a perching arm with a gripper designed to hold on to ISS handrails to maintain position without use of the propulsion system. Main operating scenarios include performing as a free-flying low-gravity research test bed, performing as a camera system recording video images of the crew, and performing surveys using external payloads and instruments. Astrobee will replace SPHERES by the end of 2017.
- Robonaut2 – humanoid robotic development project onboard the ISS. Can hold tools and assist in experiments, but mainly serves as a testbed for now.

The key advantage to the snake robot compared to the alternatives, would be the dual use as both a slender (autonomous) robot and a manipulator arm with a fraction of the complexity of a full humanoid robot. The slender design would allow access to a larger portion of ISS infrastructure while still being capable of performing physical manipulation of objects. Furthermore, the modular design would make it simple to replace a failed module and to stock spares.

A few pictures of the inside of the ISS is provided below in order to give the reader an overview of which environments a snake robot would have to operate in. Additional comments:

- There are cables, equipment, computers and other items "everywhere", e.g., in the Columbus module. Thus, there are lots of potentially fragile equipment such as camera lenses.
- ESA has provided an interesting "tour" on YouTube of the ISS from 2012 [4].

Figure 3: Robert Thirsk at the Minus Eighty Degree Laboratory Freezer. Notice the blue handles. These are examples of infrastructure that a snake robot can use for locomotion. Credit: NASA.

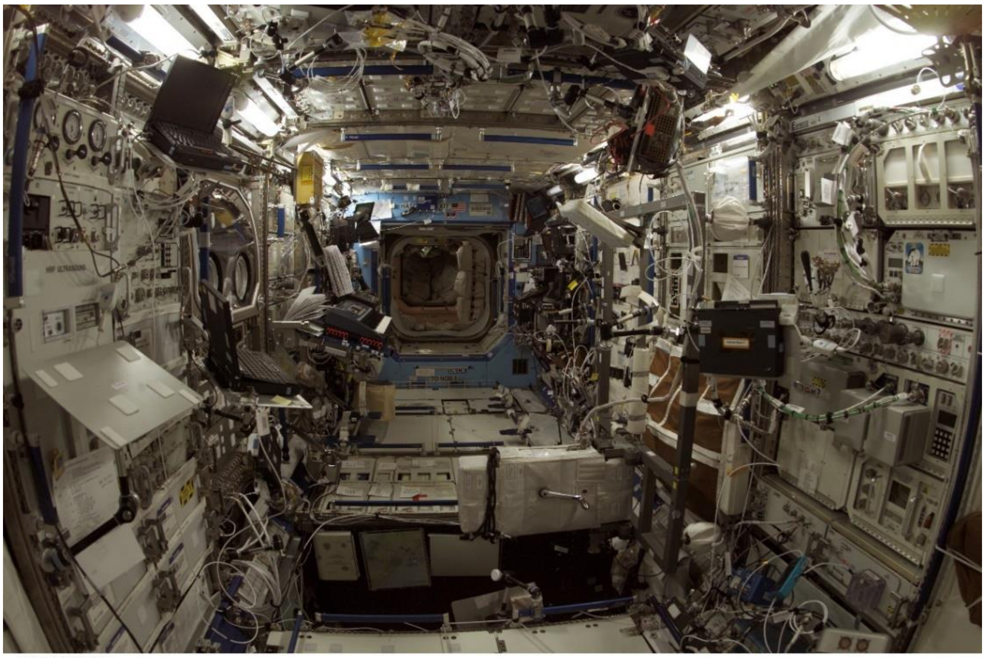


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Figure 4: Interior view of the Destiny Laboratory. Credit: NASA.

In particular, the snake robot would be able to crawl into hard-to-access spaces, such as in between and behind infrastructure. In case of autonomous operation (as depicted in Figure 5), the snake robot could have a docking station from which it could automatically detach in order to carry out scheduled inspection and intervention operations.

Figure 5: Snake robot moving about the ISS autonomously. Credit: NASA. Snake robot illustration by M. Bjerkeng / Ø.H. Holhjem, SINTEF.

If fully autonomous operation is not desired, for instance due to concerns about the maturity of the technology, the snake robot could be designed for assisted/supervised inspection and intervention tasks when the location of interest is not easily accessible to astronauts.

A main motivation for a fully autonomous concept is to relieve the astronauts of simple tedious tasks so that they can focus their attention on the more complex tasks. But equally important, careful inspection by a snake robot allows a more thorough inspection behind equipment racks and other hard-to-access spaces, thereby improving the safety of the installation. Moreover, the snake robot could also save astronauts time by for instance preparing a work site.

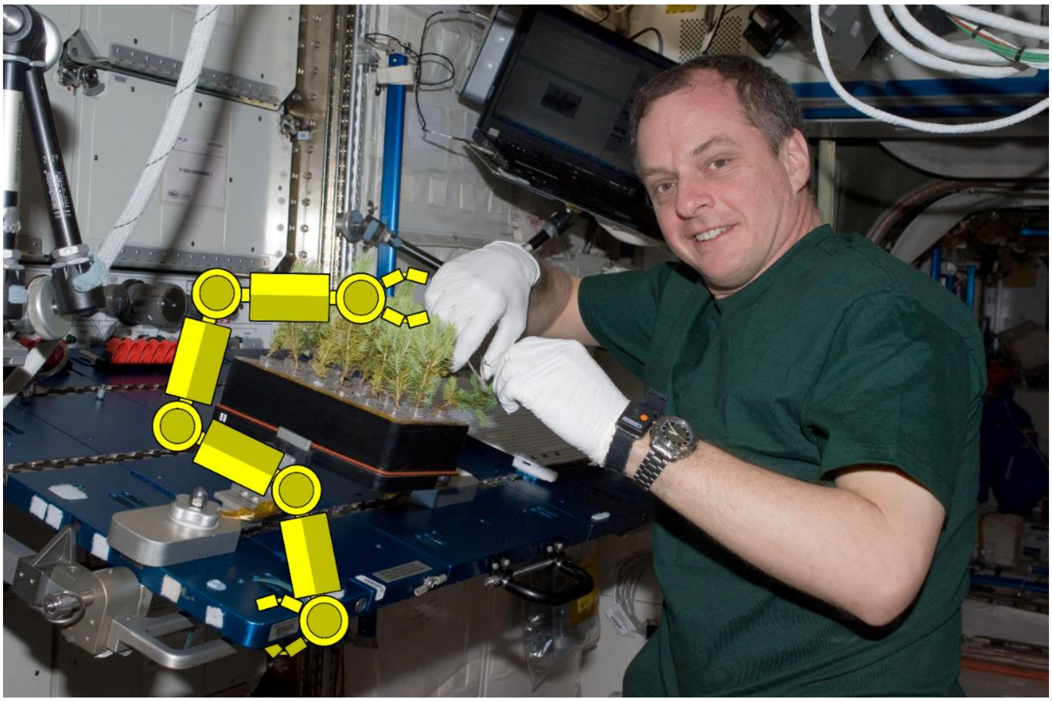

Figure 6: Illustration of a snake robot assisting in a science operation at the ISS. Credit: NASA. Snake robot illustration by M. Bjerkeng, SINTEF.

Finally, a list of possible tasks within this scenario includes the following:

- Science
  - Assist in science operations, such as providing pictures / video of experiments, holding on to items, pushing buttons, flipping switches, etc.
- Inventory
  - Search for and retrieve items inside the ISS.
  - Keep track of inventory by moving around the ISS and logging that items are in their designated positions.
- Inspection and monitoring
  - Inspect equipment both easily accessible within the ISS as well as inspections that require access to areas behind other equipment, in-between narrow gaps, etc.
  - Act as an autonomous camera platform for video recording operations and areas at the ISS. E.g., follow an astronaut around and video record his/hers work to provide a flexible video link to ground control or as part of documentation work.
  - Example operation: A snake robot that crawls along HVAC lines in order to inspect them and look for leakages or to allow inspection inside stand-off areas (which has internal volume) in the Columbus module.
- Intervention
  - Carry out simple maintenance and repair operations in between the ISS modules or other hard to access areas. Operations could include to operate handles, remove screws, push buttons and place/retrieve items.
  - Example operation: The snake robot removes a panel which is attached with a high number of screws before the astronaut appears to carry out an operation on equipment behind the panel.

The above-mentioned tasks have been inspired by [5] and [6].

3.2 Scenario 2: Planetary Exploration with Snake Robots – Specifically Lunar Lava Tubes

The use of snake robots in planetary exploration missions is attractive when the goal is to explore certain types of challenging terrain, such as very cluttered terrain, caves or lava tubes. For any type of operation across flat and easy terrain, the wheeled/tracked rovers will be much faster, more efficient and able of carrying a much larger payload than the snake robot. As the main strength of the snake robot is traversability as opposed to payload capacity and speed, any mission involving just a snake robot and a lander would require the landing site to be very close to some challenging environment (such as a lava tube) that desires further investigation. Such precise landings constitute a considerable challenge. Thus, the first realistic use of snake robots for use in planetary exploration involves collaboration with a (mobile) rover.

A cooperative rover–snake robot system can exploit the individual advantages of the two robot systems. In particular, a rover can cover rather large areas, it has a relatively high energy storage capacity, and it can transport a sample analysis station. If several tools are needed for the snake robot, the docking station on the rover should support a tool changing possibility. The rover may also need to include a repository for material samples collected by the snake robot. A snake robot, on the other hand, can access narrow and cluttered terrains in order to perform sample taking. Also, a snake robot has the ability to traverse vertical obstacles (such as a pile of rocks) to a certain extent. The overall length of the snake robot determines how large of a vertical drop it can scale. Figure 7 illustrates a possible cooperative rover-snake robot system.

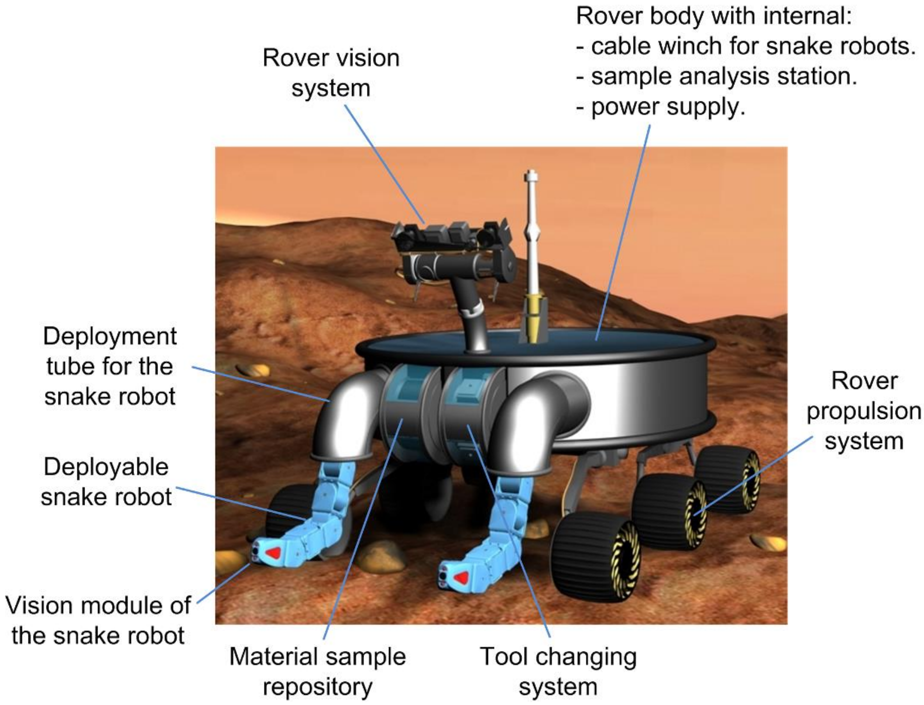

Figure 7: Conceptual overview of a rover equipped with deployable snake robots.

A tether containing power and communication lines connects the snake robot to the Rover. The tether eliminates the need both for batteries inside the snake robot and for radio communication with the snake robot for remote control. Additionally, the tether also allows the snake robot to be winched back to the rover or alternatively; provides a means for the snake robot to help the rover if stuck as illustrated in Figure 8.

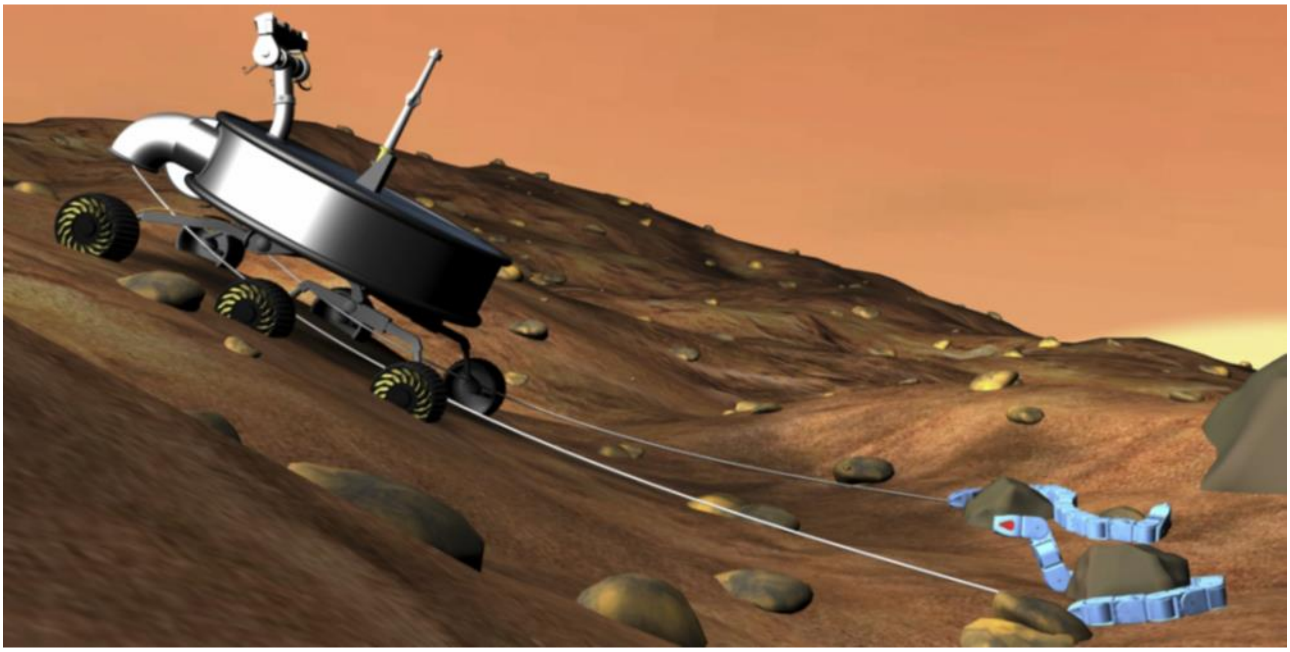

Figure 8: Illustration of two snake robots forming anchors such that the tether winch can be used in an attempt to pull the rover free from the loose sand.

The tether winch can be located inside the body of the rover, inside the snake robot, or both in the snake robot and in the rover. The advantage of having the winch inside the snake robot is that there is less need for a snake robot to pull the entire tether as the robot moves forward/backward. Instead the snake robot would feed out the tether as the robot moves forward, and wind in tether as it moves backwards again. This approach also reduces the risk of the tether getting stuck as the tether to a large degree will follow the same path as traced out by the snake robot. The disadvantage of adding a tether winch to the snake robot is size, weight and complexity of the snake robot. Furthermore, the rover should have the ability to cut the tether in case the snake robot is stuck or in some other manner endangers the entire mission. Certain missions may not allow the tethered solution, meaning that the snake robot would have to carry power generation/storage equipment and possibly return to the accompanying rover for charging and/or data download. Options for an untethered solution will be discussed in more detail in Sections 3.3 and 6.2.5 of this report. Additional illustrations of the cooperative rover–snake robot system engaged in planetary exploration are shown in Figure 9 and Figure 10.

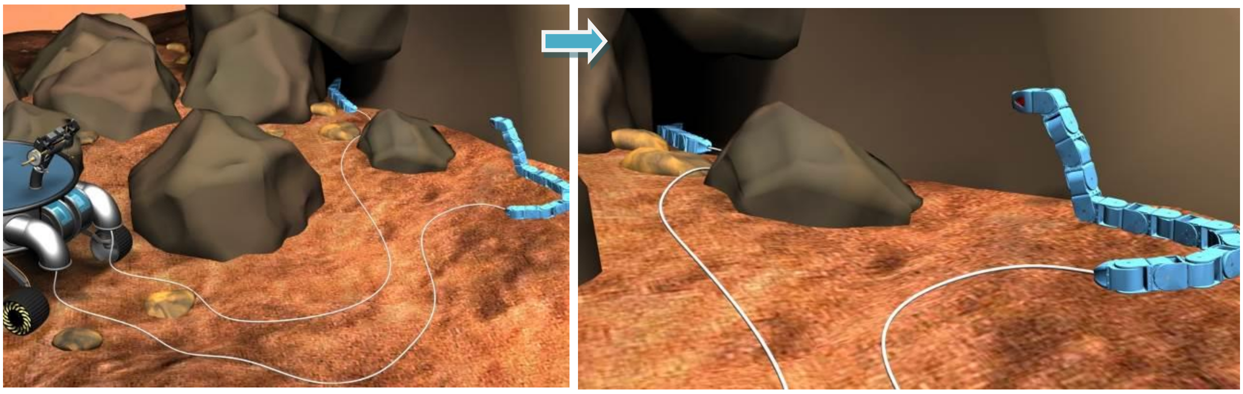

Figure 9: Illustration of two snake robots exploring a small cave.

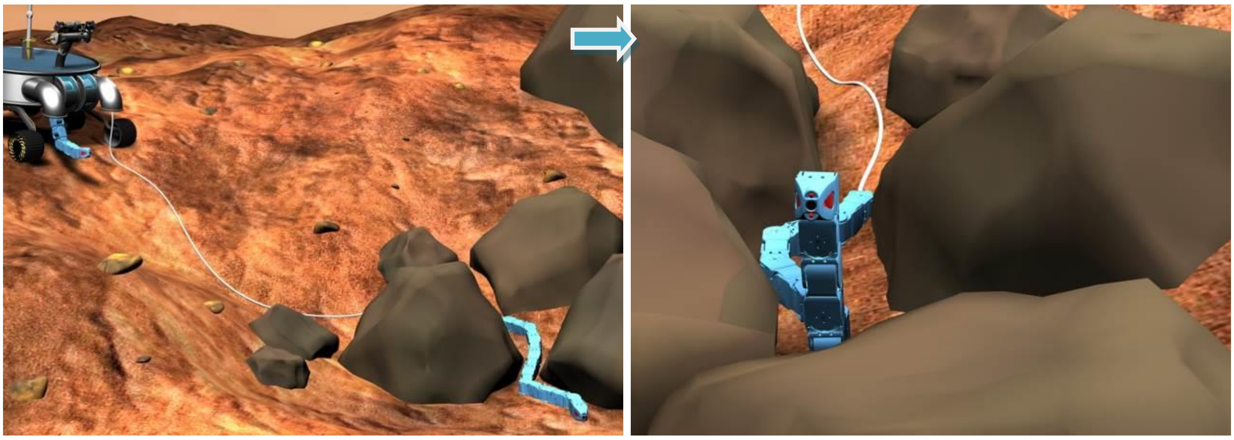

Figure 10: Illustration of a deployed snake robot that manoeuvres challenging terrain.

A specific sub-scenario tied to planetary exploration that is of particular interest currently, is the use of snake robots to explore the lava tubes on the Moon to determine if they are suited to house the first human settlements (Moon Village). An underground settlement is advantageous since the temperatures will reach a stable -20 ºC (as opposed to the extreme temperatures on the surface) and also provides protection from solar "storms", cosmic rays and the frequent micrometeor impacts. Figure 2 illustrates how the properties of a snake robot may prove to be useful during the exploration of lunar lava tubes.

3.3 Scenario 3: Snake Robots to Explore Low Gravity Bodies

The main challenge tied to exploration of low gravity bodies such as asteroids, comets or small moons, is how to successfully land/place the lander in a desirable location and furthermore how the surroundings can be explored in a controlled manner when traction is virtually absent. As opposed to Scenario 2 described above, the snake robot would not have a companion rover for the low gravity body mission, but would likely have a separate landing vehicle. In addition to protecting the robot during the landing phase, having the separate lander would have the additional benefit of limiting the amount of equipment/instrumentation necessary to carry onboard the snake robot. Competitive robotic systems for exploration of low-gravity bodies includes:

- Wheeled/tracked systems – will be limited to slow stable motion due to low traction or else uncontrollable tumbling may result.
- Hopping/tumbling systems – small and relatively simple robots that are designed to hop/tumble across the surface by spinning and breaking internal flywheels. The system can traverse reasonable fast but is limited to speeds below the escape speed of the low-gravity body.

While hopping/tumbling systems are popular for the purposes of exploration of low-gravity bodies, precise navigation is fairly difficult with these systems, and due to their size they have limited data collection abilities. A snake robot would be at an advantage if more complex missions are desired.

The European Space Agency lander Philae which in 2014 became the first spacecraft to land on a comet, failed to anchor itself to the desired landing spot after initial impact due to unexpected events (including unexpected surface properties). After bouncing off the surface, the lander came to rest in a spot shadowed from the sun, rendering it unable to use its solar panels to recharge the batteries. Philae was eventually located in an image captured by the navigation camera onboard the Rosetta Probe while orbiting Comet 67P as shown in Figure 11.

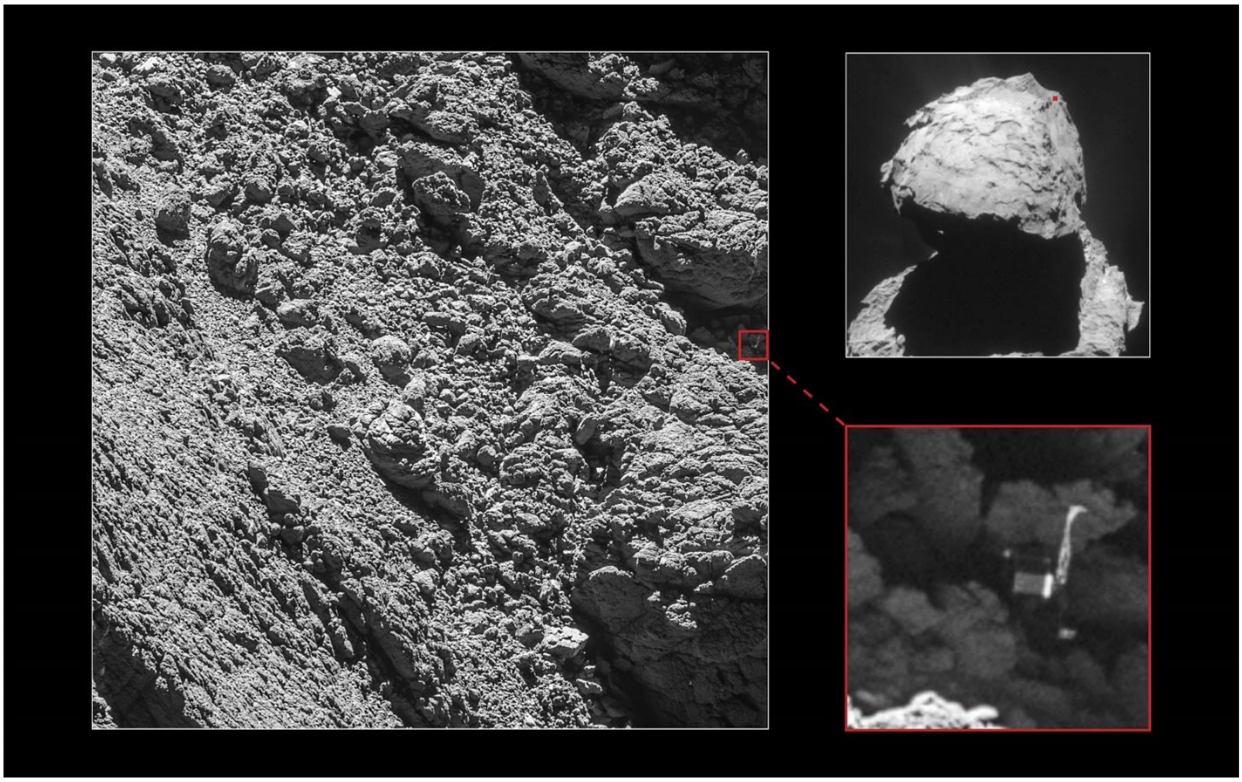

Figure 11: Philae lander on Comet 67P. Credit ESA (Main image and lander inset: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA; context: ESA/Rosetta/NavCam – CC BY-SA IGO 3.0).

Two important lessons learned from this mission should be considered in the design of a snake robot and lander system for low gravity bodies. First, the risk of a failed mission could be reduced by adding some degree of power independence between the lander and the snake robot. Second, the snake robot locomotion should be efficient for different types of surfaces and terrain. As evident by the image from Comet 67P above, the landscape can be extremely challenging to traverse. Locomotion planning onboard the snake robot could select the optimal locomotion strategy given measurable inputs such as gravity field, terrain profile, surface firmness and surface roughness.

For mission flexibility, the snake robot could be tethered to the lander to perform the initial part of the mission, but have the ability to sever the tether for more autonomous operation if/when desired.

3.4 Scenario 4: A Snake Robot as an Astronaut's Extended Arm

This concept addresses how a snake robot can be used as an "extended arm" for an astronaut. The main idea is that an astronaut holds one end of a snake robot (denoted the "fixed end"), while the other end of the robot (denoted the "tooling end") performs an operation with an inspection/intervention tool. Such tools could include a camera, a screw-driver or a gripping mechanism for grasping and possibly turning items.

This scenario provides the astronaut with the ability to extend the reach of his/her arms, as well as to provide access to narrow/cramped places.

It is important that the snake robot provides an intuitive human-machine interface. This will ensure that the astronaut who operates the snake robot is able to carry out his/her intended operation with high quality and efficiency.

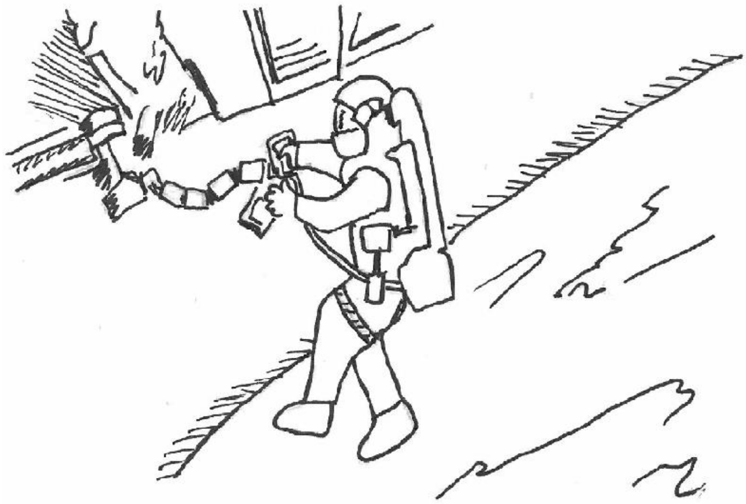

Figure 12: Artist rendition of an astronaut using a snake robot as an extended arm outside a space installation. Actual use will benefit from, e.g. that the astronaut is somehow attached to the installation. Illustration by M. Bjerkeng, SINTEF.

The snake robot can be fitted with a range of technologies to ensure efficient and intuitive operations. These are listed next.

- Perception: Robot vision in order to automatically guide a tool towards the desired location. E.g., automatically detect screws to relieve the astronaut in having to fine-position the screw-driver mounted on the tooling-end of the snake robot.
- Voice control: The astronaut can command the snake robot with voice commands such as "move towards screw".
- Direct control: Utilize technology for reading control commands for prosthetic devices (e.g., read muscle contractions) in order for operators to intuitively control the snake robot.
- Display: A small display is mounted on the fixed end of the snake robot. A camera is mounted on the tooling end of the snake robot. The astronaut can monitor operations by looking at the display in the cases where the astronaut cannot see the tooling end directly (such as for operations where the tooling end is inside a narrow passage).

Finally, operations involving the tightening of a screw requires that the screwdriver maintains a certain amount of normal force in order to avoid that the screwdriver slips out of the screw. It can be challenging to be able to apply such necessary normal force since the astronaut holds on to the snake robot at a place possibly quite far from the screw driver (if the snake robot is somewhat long). A possible way to address this challenge is that the snake robot uses parts of its body to push against infrastructure in order ensure that the tip of the screwdriver stays connected to the screw.

3.5 Scenario 5: A Snake Robot for Logistics Operations.

This concept addresses how a snake robot can be used to autonomously transport items between locations inside or outside the ISS. For instance, a snake robot could be designed to transport small to medium items attached to one/some of its middle link segments. Since astronauts can move items around quite easily, this scenario would only be relevant in case the astronauts would benefit from having an autonomous transport mechanism (i.e., an autonomous package delivery system) that could take care of logistics so that the astronauts can focus on more high-level tasks.

Mobility is achieved in a similar fashion as for the concept for autonomous routine inspections and interventions.

3.6 Scenario 6: A Snake Robot as an Astronaut's Co-worker

This concept addresses how a snake robot can act as an assistant/co-worker to astronauts in their work at the ISS, including that a snake robot can be used as a multi-functional assisting device. Hence, a snake robot basically acts as an astronaut's "advanced third arm". One end of the snake robot would either be attached to the astronaut, or to the ISS. We denote this end of the snake robot the "fixed end". The other end of the snake robot – the tooling end – can for instance be used to hold a torch, hold a procedure/manual or hold on to parts that have been removed. The rest of the snake robot body can also be used for attaching parts/tools/etc. that the astronaut may need during operations.

For this concept to be useful, it is imperative that the snake robot is easy to attach and detach to/from the astronaut or infrastructure on the ISS, and also that the snake robot behaves intuitively such as to automatically adjust position to allow a clear path for the light if it is used as a light source.

4 Concepts for Selected Scenarios

As described in the previous section, the following three scenarios have been selected for further consideration:

- Scenario 1: Snake robots to perform inspection and intervention tasks on-board the ISS, such as to inspect the hard-too-see spaces behind the equipment racks.
- Scenario 2: Snake robots for planetary exploration, specifically to explore "lava tubes" on the Moon to determine if they are suited to use as enclosures for a permanently inhabited base.
- Scenario 3: Snake robots to explore low gravity bodies such as asteroids.

For each of the three selected scenarios we detail a corresponding snake robot concept by elaborating on the functionality that is required for a snake robot to carry out the particular scenario. A **concept** is a brief overview of a snake robot mechanism which focus on certain abilities with a snake robot. E.g., a long, slender and light-weight snake robot arm that can function as a robot manipulator. The general functionality that will be required for any snake robot mission is summarized in Section 4.1. The scenario-specific functionality is outlined in sections 4.2 through 4.4, dedicated to each of the scenarios listed above. We employ the following function categories:

- Sensing and perception
- Mechatronics
- Mobility
- Human-machine interfaces

4.1 General Snake Robot Functions

This section describes the functions that a snake robot platform has to have for space operations regardless of scenario.

<u>Sensing and perception</u>

Enable the snake robot to understand its environment and its relation to the environment.

Function	Description	Challenges
Proximity detection	Environment awareness in order to avoid unwanted contact with the environment (i.e., collisions). Could include sensors along the snake robot's body.	Miniaturization of sensors. Increased system complexity by adding more sensors.
Object pose estimation	Determine position and orientation of objects in order to enable, e.g., grasping or in connection with relative navigation for docking.	Challenges for 3D pose estimation include varying backgrounds, varying light conditions, blank surfaces.
Mapping	Build 3D maps of its surroundings in order to facilitate robot localization and motion/mission planning.	Need to obtain overview of terrain either from rover or else the snake robot must be designed with some type of "survey surroundings" mode where it stands up tall.
Robot absolute pose estimate	Determine position and orientation of a snake robot relative to a suitable "global" coordinate frame.	Pose estimation to be achieved without external infrastructure such as radio beacons or markers.

Speed estimation	Determine speed of the robot relative to its environment.	Environment conditions may decrease accuracy of speed estimation with image based technologies.
Item identification	Have the ability to identify required items (mission/scenario specific).	RFID-tagged equipment would be easier to identify compared to items that are not tagged.
Measure temperature	Measure the temperature of the surroundings.	
Measure surface characteristics	Have the ability to determine key surface characteristics in order to determine which type of locomotion that is best suited. Key technologies are contact force sensing and accelerometers.	Challenging to characterize a wide range of different surfaces.
Contact sensing	Detect physical contact between the snake robot and the environment and also estimate the size of the force at the point(s) of contact.	Challenging to obtain high quality contact force detection for the entire robot body.
Illumination Management	Be able to determine if there is sufficient light available to complete the mission satisfactory. (If not, the robot needs to provide additional light).	

<u>**Mechatronics**</u>

Provide the necessary mechanic and electronic systems to enable the snake robot to carry out intended operations.

Function	Description	Challenges
Joint actuation	Actuator and gear to rotate each snake robot joint.	Depending on how small cross section a snake robot on the ISS should have, miniaturization of actuator-gear systems with sufficient torque may be a challenge.
High-friction contact	Provide high-friction contact between the snake robot and its surroundings. For instance, by covering some parts of the snake robot with high-friction rubber, or Gecko-like materials.	There are many different types of surfaces – how to ensure high friction contact with many of them? Also, need to ensure simple release.
Store and transport small objects	Provide storage capability on the snake robot in order to store small objects. For instance, one of the links on the snake robot could contain a small compartment in which the snake robot could place items.	Space and weight constraints.

On-board computing and data storage	Enable computations onboard the snake robot. The computations will likely include low-level joint control, planning algorithms, perception algorithms, safety monitoring. Also, some amount of data storage is required.	
Communication between snake robot and communication hub	Enable communication of data between the snake robot and the main data recipient via a communication hub.	Un-tethered communication from the inside of a lava tube (or similar) may dampen communication signal.
On-board energy supply (non-tethered)	The non-tethered snake robot must have the ability to store and/or generate energy on board.	Weight and space limitations.
Modularity	The robot should be constructed by assembling several (nearly) identical modules for simple construction, modification and maintenance as well as for purposes of redundancy.	
Winch (tethered)	If the snake robot is tethered, a winch should tend the tether.	May be difficult to house the winch on the snake robot due to weight/space constraints. Risk of snagging and rupture increases by keeping winch onboard rover/lander.
Cutter (tethered)	If the snake robot is tethered, it should be possible to sever the tether if it is deemed necessary.	
Illumination Management	Be able to provide additional light if needed.	
Environment Protection	Be able to provide structural protection of delicate internal components as well as to provide protection against and the harsh environment.	Protection against extreme temperatures given the small size of the snake robot for planetary exploration scenarios.
Charging and storing	Provide a docking capability which allows for charging and gives a designated place for storing the snake robot while not in use. The docking station could also be used for, e.g., high-bandwidth data transfer.	Need to make sure the robot can make it back to the docking station before its battery depletes.

Mobility

Ensure that the snake robot is able to move between locations.

Function	Description	Challenges
Path Planning	Use available information about mission goal, map of surroundings, position information and system limitations to determine the optimal path forward.	
Locomotion Planning	Determine the most suited type of locomotion to use for each segment of the optimal planned path, and switch between and combine different types of locomotion if necessary.	
Locomotion Type Switch	The robot has to be able to transition between two locomotion types automatically as needed, without disrupting the mission.	
Climbing	The ability to scale vertical objects and climb over a pile of rocks is one of the key advantages of the snake robot.	

Human-machine interfaces (HMI)

Ensure that humans can monitor and control snake robot operations.

Function	Description	Challenges
Interaction with command center	Provide user interfaces at a command center which can be used to monitor and control the snake robot.	Provide intuitive human-robot-interaction.

4.2 Concept 1 (C1): Inspection and Intervention Onboard the ISS

In this section, we describe the functions that a snake robot would need to carry out in order to form a platform suitable for inspection and intervention tasks onboard the ISS. A general challenge for all types of operations onboard the ISS involves the risk of damaging other equipment. An example would be that the snake robot grabs onto a camera lens instead of a handrail, and pushes buttons or flip switches unintentionally. Hence the robot perception is critical for a successful design. Furthermore, the robot's exterior needs to be designed in a way that reduces the risk of the snake robot damaging its environment.

Sensing and perception

Enable the snake robot to understand its environment and its relation to the environment.

Function	Description	Challenges
Marker pose estimation	Determine position and orientation of markers in order to enable, e.g., grasping or in connection with relative navigation for docking.	Extra work with adding markers on designated places within the ISS.

Video feed	Provide live video feed(s) from the snake robot to both command centers both at the ISS and on earth, and/or store video data.	

Mechatronics

Provide the necessary mechanic and electronic systems in order to enable the snake robot to carry out operations at the ISS.

Function	Description	Challenges
Inherently safe joint movement	A robot joint mechanism to prevent the robot from being able to harm equipment or personnel. An example is to design the robot using compliant joints.	Difficult to achieve while at the same time satisfying all the performance requirements.
Collision absorption	Provide a robot exterior that absorbs much of the forces involved in possible collisions between the snake robot and its environment. This is typically done using impact foam.	Impact foam may increase diameter of snake robot, thus limiting access to narrow gaps. Exterior foam will also restrict how much the joints can bend.
Anchor to the ISS	Provide means to anchor to the ISS. For instance, by gripping the handrails, or to attach to the walls (e.g., by having some sort of adhesive surface on the snake robot, using magnets, or making use of Velcro attached many places at the ISS).	Difficult to stop rotational motion by holding on to a single handrail. Magnets may interfere with scientific equipment? Velcro has limited hold.
Grip and intervention capability	Provide the snake robot with the physical components necessary to grip objects and its environment. The purpose could be to anchor the snake robot, or to intervene with an item/object such as to flip a switch or to move an item from A to B. To carry out grab-pull-push locomotion it could be beneficial for the gripper to have a somewhat compliant and high-friction surface. This could result in a more rotation-stable grip.	Design a low-complexity multi-purpose gripper.
Communication between snake robot and ISS/ground station	Enable communication of data between the snake robot the ISS and ground command center. This could be achieved via WiFi onboard the ISS and via Ku-band between the ISS and the ground station.	Is there sufficient coverage of e.g. WiFi behind and in between ISS modules?

Operate tools	Be able to operate tools such as an electric screwdriver. This would require the tool handle to be specifically designed for a snake robot gripper, or it could require some sort of mechanical interface and possibly an electrical interface needs to be designed to function as an interface between a standard tool and the snake robot gripper.	A snake robot might require special tools not suitable to be operated by humans. It may be challenging to find a good way to store tools in case the snake robot needs to change between tools during an operation.
Interact with objects on the ISS	After the snake robot has determined the pose of an object or point of interest, it should be able to move its body such that its tool gets close enough in order to carry out an intended operation (such as retrieving an object, loosening a screw, etc.). Such operations will require the snake robot to anchor parts of its body in order to provide the necessary forces and torques to carry out its intended operation.	Obtain sufficient anchoring. Grasp objects. Apply correct amount of force in an operation to avoid damaging equipment, for instance by breaking a switch.

Mobility

Ensure that the snake robot is able to move between locations at the ISS.

Function	Description	Challenges
Hand-over-hand locomotion	The snake robot has attached one of its ends to the ISS (for instance by holding on to a handrail with a gripper). It uses the counter forces in the contact point to reorient itself and reaches its other end toward a new anchoring point (such as a new handrail or a place with Velcro). Once attached to its new anchoring point it releases its grip on the first contact point.	This form of locomotion sets hard constraints on the length of the snake robot and/or the distance between possible anchoring points. It may be necessary to take a detour (which has a sequence of anchoring points that are in reach) on its way towards a desired target. Moreover, it might be a challenge if both ends are attached to Velcro.
Grab-fold-push locomotion	Temporarily attach one end of the snake robot to the ISS (for instance by holding on to a handrail) and pull the snake robot towards the of attachment point such that it "folds". Orient the snake robot in a desired direction. Somewhat quickly "unfold" the snake robot and release its attachment to the handrail. Then the snake robot flies toward its next anchoring point.	The snake robot may require a solid grip on a handrail in order to orient the snake robot after it has folded its body.

Contact-fold-push	The snake robot flies towards a surface on the ISS. The front end comes into contact with the ISS surface. The snake robot then moves its body such that it pulls or pushes (depending on which direction it would like to go) its body towards its next contact point. This form of locomotion would require some sort of high-friction contact point between the snake robot and the ISS, such as covering certain parts of the snake robot with rubber, and then make contact with metal surfaces on the ISS.	The snake robot needs to act compliant when touching ISS surfaces such that the robot does not immediately bounce off, but is able to keep the contact while the snake robot utilizes the contact in order to move in a desired direction.
Concertina locomotion	Locomotion through narrow corridors. Anchor front end of the snake robot by moving its joints such that it pushes against both sides of the corridor. Pull back-end of snake robot towards the front such that the snake robot "folds". Anchor the front end and straighten the snake robot body. Repeat the whole procedure.	Requires quite narrow corridors. Need to control contact forces such that the snake robot does not damage ISS equipment by pushing too hard against it.

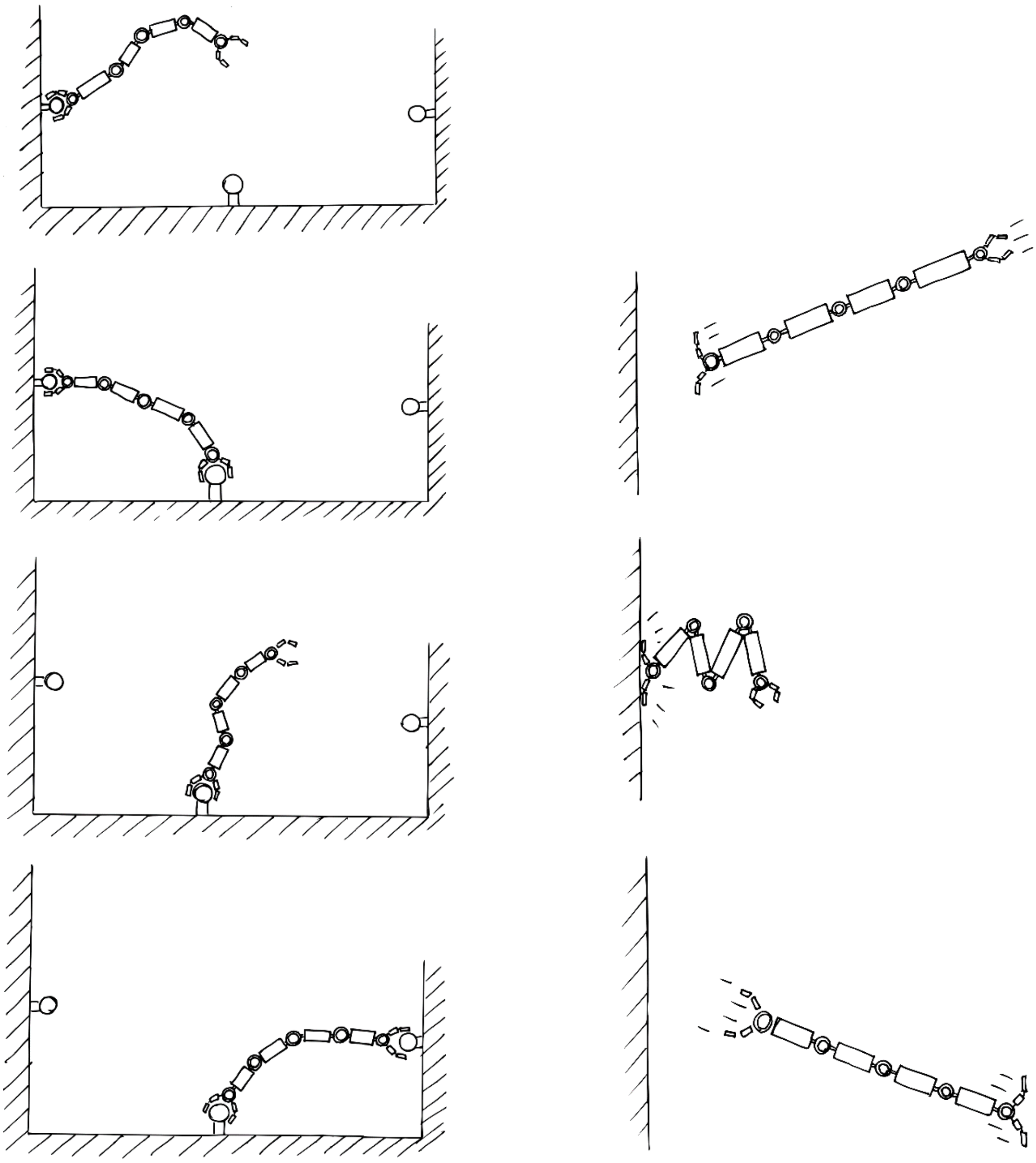

Figure 13: (left) Hand-over-hand locomotion, (right) contact-fold-push locomotion. Illustration by M. Bjerkeng, SINTEF.

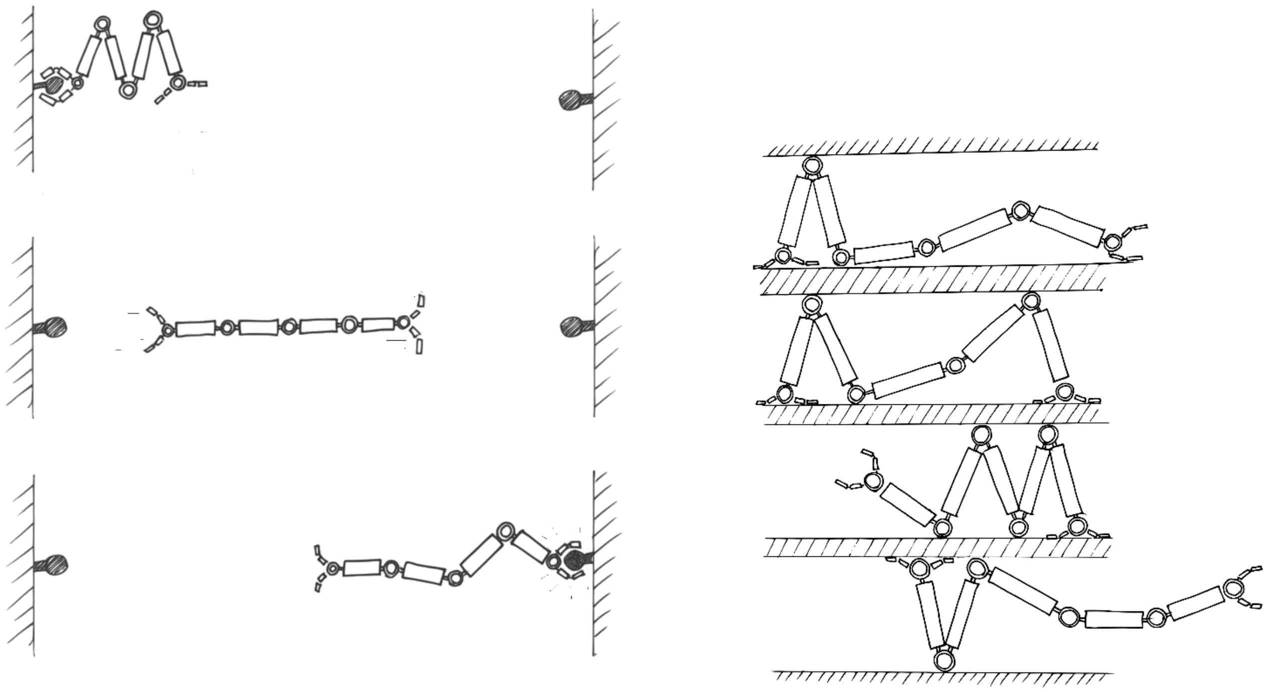

Figure 14: (left) Grab-fold-push locomotion, (right) concertina locomotion. Illustration by M. Bjerkeng, SINTEF.

<u>Human-machine interfaces (HMI)</u>

Ensure that humans can monitor and control snake robot operations.

Function	Description	Challenges
Proximity interaction with astronauts	Interact with astronauts close to the snake robot in order to receive commands from the astronauts and provide feedback to them. The feedback could include sound, light, displays, etc.	Provide intuitive human-robot-interaction.

4.3 Concept 2 (C2): Exploration of Lunar Lava Tubes

The scenario assumes snake robot planetary exploration where a companion rover provides transportation across longer distances and also houses both the main data analysis station and the energy generation and storage functionalities. The snake robot can then be specially designed to be slender and highly manoeuvrable, allowing it to enter challenging terrain formations unavailable by other means, such as a lava tube. The snake robot could be designed to operate with or without a tether, but the tether would greatly increase the duration of the mission as well as the data collection capability. In this section, we describe the functions that a snake robot would need to carry out in order to form a platform suitable for exploration of lunar lava tubes.

<u>Sensing and perception</u>

Enable the snake robot to understand its environment and its relation to the environment.

Function	Description	Challenges
Video feed	Provide live video feed(s) from the snake robot to the docking station.	Bandwidth of non-tether solution is probably limited.

Identify sample	Identify objects suitable for sample collection.	Low contrast between objects and background. Bandwidth of non-tether solution is probably limited.
Other mission specific sensing technologies	Sensing technologies based on the requirements for the scientific mission.	

Mechatronics

Provide the necessary mechanic and electronic systems in order to enable the snake robot to carry out intended operations.

Function	Description	Challenges
Grip and intervention capability	Provide the snake robot with the physical components necessary to grip objects and its environment. This allows the robot to perform tasks such as getting free of obstacles or collecting items.	
Non-tethered: On-board energy generation	Include some energy generation capability as a backup solution in case the untethered snake robot fails to return to the rover in time.	Space and weight constraints
Sample Collection	After the snake robot has determined the pose of an object or point of interest, then it should be able to move its body such that its gripper gets close enough in order to carry out an intended operation. Such operations might require the snake robot to anchor parts of its body in order to provide the necessary forces and torques to carry out its intended operation.	May be difficult to ensure that the item to collect is within allowable size and weight requirements.

Mobility

Ensure that the snake robot is able to move between locations.

Function	Description	Challenges
Locomotion	Ability to perform each of the following types of motion (described in Section 2.4) or a combination of these: - Lateral Undulation - Concertina Locomotion - Rectilinear Crawling - Sidewinding	

Climbing	Ability to scale a vertical object with a height of at least TBD of its body length.	

Human-machine interfaces (HMI)

HMI should be designed based on operational requirements. This is out of scope of this report.

4.4 Concept 3 (C3): Exploration of Low Gravity Bodies

As the snake robot cannot rely on assistance from a rover during the exploration of low gravity bodies, more functionality must be carried onboard the snake robot. Assuming that the snake robot is tethered to the lander, much of the energy generation/storage as well as the data analysis functionality could be housed in the lander. However, the snake robot should carry a minimum set of all required functionalities onboard in case of failure of the lander either during impact or due to the landing site being shadowed from the sun.

Two types of snake locomotion are of particular interest for this scenario. The sidewinding employed by desert snakes in loose sand and the rectilinear crawling. While the rectilinear crawling is much slower than other types of locomotion, slow and controlled motion may be a good choice in a low gravity environment where the surface features and texture is not well known. One may even consider to add some caterpillar features for additional gripping capability. The caterpillar rectilinear crawling is facilitated with six thoracic legs forward and suction-cup legs (prolegs) toward the rear that is used to cling on to things.

In this section, we describe the functions that a snake robot would need to carry out in order to form a platform suitable for low gravity exploration tasks.

Sensing and perception

Enable the snake robot to understand its environment and its relation to the environment.

Function	Description	Challenges
Video feed	Provide live video feed(s) from the snake robot to the lander/orbiter.	Bandwidth of non-tether solution is probably limited.
Identify sample	Identify objects suitable for sample collection.	Low contrast between objects and background. Bandwidth of non-tether solution is probably limited.
Other mission specific sensing technologies	Sensing technologies based on the requirements for the scientific mission.	

Mechatronics

Provide the necessary mechanic and electronic systems in order to enable the snake robot to carry out intended operations.

Function	Description	Challenges
Grip and intervention capability	Provide the snake robot with the physical components necessary to grip objects and its environment. This allows the robot to perform tasks such as getting free of obstacles or collecting items. To carry out grab-pull-push locomotion it could be beneficial for the gripper to have a somewhat compliant and high-friction surface. This could result in a more rotation-stable grip.	
On-board energy generation	Include some energy generation capability as a backup solution in case the untethered snake robot fails to return to the rover in time.	Space and weight constraints.
Sample Collection	After the snake robot has determined the pose of an object or point of interest, then it should be able to move its body such that its gripper gets close enough in order to carry out an intended operation. Such operations might require the snake robot to anchor parts of its body in order to provide the necessary forces and torques to carry out its intended operation.	May be difficult to ensure that the item to collect is within allowable size and weight requirements.

Mobility

Ensure that the snake robot is able to move between locations.

Function	Description	Challenges
Locomotion	Ability to perform each of the following types of motion (described in Section 2.4) or a combination of these: - Lateral Undulation - Concertina Locomotion - Rectilinear Crawling - Sidewinding	
Climbing	Ability to scale a vertical object with a height of at least TBD of its body length.	

Human-machine interfaces (HMI)

HMI should be designed based on operational requirements. This is out of scope of this report.

5 Overview of Requirements for Identified Concepts

This chapter summarizes preliminary high-level system requirements based on the three concepts described in Section 4. Note that the development of these requirements has mainly been a tool to arrive at a more detailed snake robot concept for the three candidate scenarios, and that no complete analysis have been performed to ensure that all relevant requirements are covered. The requirements below should be viewed as a starting point for a more detailed set of requirements for a snake robot for space applications. The table below consist of 4 columns with the following content:

Column 1 – Requirement ID.

Column 2 – Includes a reference to the applicable function among the ones identified in Section 4.

Column 3 – Provides a reference to the relevant concepts, i.e. not all the requirements will be relevant for all three concepts.

Column 4 – Requirement text.

Note the following distinction between the words "shall" and "should":

Shall – Means that the requirement is mandatory.

Should – Means that the requirement is desired but not mandatory.

Also, TBD (To Be Determined) are placeholder for performance parameters/values that will need to be determined once specific aspects of the mission has been determined.

ID	Reference to system functions	Relevant concept	Requirement text
			SENSING AND PERCEPTION
Sen 1	Proximity detection	1, 2, 3	The robot **should** be able to avoid unwanted contact with the environment. *Comment: See also req. Mec 5.*
Sen 2	Object pose estimation	1, 2, 3	The robot **shall** be able to determine position and orientation of objects.
Sen 3	Marker pose estimation	1	The robot **shall** be able to use markers for navigation.
Sen 4	Mapping	1, 2, 3	The robot **should** be able to build and store a 3D map of its surroundings.
Sen 5	Robot absolute pose estimate	1, 2, 3	The robot position **shall** be determined relative to a coordinate frame fixed to an absolute reference.
Sen 6	Speed estimation	1, 2, 3	The speed of the robot **shall** be determined relative to its environment.
Sen 7	Video feed	1, 2, 3	The robot **should** be able to provide live video feed.
Sen 8	Item identification	1, 2, 3	The robot **shall** be able to identify required items (mission/scenario specific). *Comment: For instance, by means of RFID or bar codes.*
Sen 9	Identify sample	2, 3	The robot **shall** be able to identify objects suitable for sample collection.
Sen 10	Measure temperature	1, 2, 3	The robot **shall** be able to measure the temperature of its surroundings.

Sen 11	Measure surface characteristics	1, 2, 3	The robot **shall** be able to measure/assess the firmness of the surface it is passing over. Note, the information will be used to select type of locomotion.
Sen 12	Measure surface characteristics	1, 2, 3	The robot **shall** be able to measure/assess the roughness of the surface it is passing over. Note, the information will be used to select type of locomotion.
Sen 13	Illumination Management	1, 2, 3	The robot **shall** be able to measure the amount of light available for the purpose of adding light if/when necessary.
Sen 14	Contact Sensing	1, 2, 3	The robot **shall** be able to detect physical contact between the snake robot and the environment.
Sen 15	Contact Sensing	1, 2, 3	The robot **shall** be able to estimate the size of the force at points where the snake robot is in physical contact with the environment.
MECHATRONICS			
Mec 1	No reference	1, 2, 3	The robot **shall** have a diameter between **TBD** and **TBD**.
Mec 2	No reference	1, 2, 3	The total length **shall** maximum be **TBD**.
Mec 3	No reference	1, 2, 3	The robot **shall** have a maximum weight of **TBD**.
Mec 4	Joint actuation	1, 2, 3	Each snake robot joint **shall** have actuators and gears to allow joint rotation.
Mec 5	Inherently safe joint movement	1	The robot including the joints **shall** be inherently safe, i.e. not capable of causing harm to equipment, personnel or itself.
Mec 6	Collision absorption	1	The robot **shall** not cause harm to the environment if a collision occurs. *Comment: For example by means of a robot exterior that absorbs collision forces and low relative speed.*
Mec 7	High friction contact	1, 2, 3	Parts of the robot **shall** be equipped with high friction material in order to support mobility.
Mec 8	Charging and storing	1, 2, (3)	A docking capability **shall** be provided for charging and storage of the robot.
Mec 9	Anchor to the ISS Grip and intervention capability	1, 2, 3	The robot **shall** be able to grip objects and fixtures. *Comment: For example by using the gripper, magnets or adhesive surfaces. The rationale is for example anchoring or to carry out grab-pull-push locomotion.*

Mec 10	Grip and intervention capability Interact with objects on the ISS	1	The robot **shall** be able to intervene with objects, such as: • Have the ability to apply a minimum force of **TBD** N in any direction. • Have the ability to apply a minimum torque of **TBD** Nm. • Move an object with maximum size **TBD** and maximum weight **TBD** into a new desired location. *Comment: For example to flip a switch. Derived requirements for mobility, tools and operations will be needed.*
Mec 11	Sample collection	2, 3	The robot **shall** be able to collect a sample with maximum size **TBD** and maximum weight **TBD**. *Comment: Note that "collect" entails both the act of gripping the sample and the act of placing it into a safe storage location.*
Mec 12	Store and transport small objects	1, 2, 3	The robot **should** be able to store and transport items with maximum size **TBD** and maximum weight **TBD**.
Mec 13	On-board computing and data storage	1, 2, 3	The robot **shall** have an on-board computer. *Comment: Typical tasks for the computer are sensor interface, low-level joint control, planning algorithms, perception algorithms and safety monitoring.*
Mec 14	Communication between snake robot and ISS/ground station	1, 2, 3	The robot **shall** communicate with ISS and/or the ground station with minimum bandwidth **TBD**. *Comment: E.g. via WiFi on board the ISS and via Ku-band between the ISS and the ground station.*
Mec 15	On-board energy supply (non-tethered)	1, 2, 3	The non-tethered robot **shall** have on board energy storage. *Comment: For example chargeable batteries.*
Mec 16	On-board energy generation	2,3	The robot **should** include on-board energy generation (e.g. solar arrays) as backup in case the robot fails to return to docking station in time or if all other sources of energy is unavailable (lander positioned in shadow).
Mec 17	Modularity	1, 2, 3	The robot **should** be constructed by assembling several identical modules (typically each robot segment will be a separate module) or at least assembled by means of combining a small number of different types of modules such as a "head module", "body module", "tail module" or "legged module".
Mec 18	Modularity	1, 2, 3	The failure of any one module **shall** not result in automatic loss of any other modules.
Mec 19	Winch	2, 3	The tethered robot and/or accompanying docking station **shall** house a winch to tend the tether. Note that housing the winch on the robot will reduce the chance of the tether getting stuck.

Mec 20	Cutter	2, 3	The tethered robot and or accompanying docking station **should** be able to cut the tether if desired.
Mec 21	Illumination Management	1, 2, 3	The robot **shall** be able to provide enough light to complete the mission objectives (i.e. to capture meaningful video or identify and secure suitable sample).
Mec 22	Operate tools	1	The robot **shall** be able to operate tools. *Comment: For example an electrical screwdriver. Might require special tools or tool interfaces.*
Mec 23	Interact with objects on the ISS	1	See req. Mec 9 and Mec 10.
Mec 24	Environment Proctection	1, 2, 3	The robot **shall** be able to protect the all its components from being damaged by the expected (harsh) operating environment.
MOBILITY			
Mob 1	Path Planning	1, 2, 3	The robot **shall** determine the optimal path forward based on the desired end position, updated data about the surroundings and current robot states. *Comment: The "optimal" path ought to consider at least the following:* • *Power consumption* • *Time to get there* • *Obstructions* • *Time to return to the charging station (if non-tethered)*
Mob 2	Locomotion Planning	1, 2, 3	The robot **shall** determine the optimal locomotion strategy in order to follow the selected path. *Comment: The "optimal" locomotion strategy ought to consider at least the following:* • *Power consumption* • *Time to get there* • *Obstructions* • *Surface details/firmness*
Mob 3a	Locomotion Types	1	The robot **shall** be able to perform the following locomotion strategies: • Hand-over-hand • Grab-fold-push • Concertina • Contact-push

Mob 3b	Locomotion Types	2	The robot **shall** be able to perform the following locomotion strategies: • Concertina • Lateral Undulation • Sidewinding • Rectilinear Crawling
Mob 3c	Locomotion Types	3	The robot **shall** be able to perform the following locomotion strategies: • Lateral Undulation • Sidewinding • Rectilinear Crawling
Mob 4	Locomotion type switch	1, 2, 3	The robot **shall** be able to transition between two locomotion types automatically, without disrupting the mission.
Mob 5	Modularity	1, 2, 3	The robot **shall** be able to achieve locomotion in the desired direction even if **TBD** of the modules fail to operate.
Mob 6	Climbing	1, 2, 3	The robot **shall** be able to scale a vertical object with a height of at least **TBD** of its body length.
Mob 7	Climbing	1, 2, 3	The robot **shall** be able to traverse an inclined surface with a minimum angle of **TBD** degrees assuming a minimum friction coefficient of **TBD.**
HMI			
HMI 1	Proximity interactions with astronauts	1	The robot **shall** have a user interface for the astronauts close to the robot. *Comments: For example lights, displays, sound, voice.*
HMI 2	Interaction in command center onboard the ISS	1	The robot **shall** have a remote user interface inside the ISS for control and monitoring.
HMI 3	Interaction with ground command center.	1	The robot **shall** have a remote user interface at a ground command center for control and monitoring.

6 Core Technologies and Potential for Realization

Based on the concepts and requirements derived in Sections 4 and 5 of this document, the core technologies that are necessary to realize the snake robot systems have been identified. They are summarized in Table 4, along with an assessment of the maturity of the technology for each of the three concepts considered. Three different maturity levels are adopted:

- Level 1 – Immature technology, potential show-stoppers
- Level 2 – Some development of the technology required, but no expected show-stoppers
- Level 3 – Mature technology, no expected implementation problems

Table 4: Core technologies necessary to realize snake robot concepts.

Technology	Maturity Level			Comments
	C1	C2	C3	
SENSING AND PERCEPTION				
Proximity detection	2	2	2	Refer to discussion in Section 6.1.1.
Object pose estimation	2	-	-	Refer to discussion in Section 6.1.2. Considered core technology for ISS scenario only.
Robot absolute pose estimate	2	2	2	Refer to discussion in Section 6.1.3.
Contact sensing	2	2	2	Refer to discussion in Section 6.1.4.
Inherently safe joint movement	2	-	-	Core technology for ISS scenario only. Refer to discussion in Section 6.1.5.
Marker pose estimation	3	-	-	Core technology for ISS scenario only.
Item identification	3	-	-	Core technology for ISS scenario only.
MECHATRONICS				
Joint actuation	2	1	1	Refer to discussion in Section 6.2.1.
High Friction Contact	2	2	2	Refer to discussion in Section 6.2.2.
Collision absorption	2	-	-	Core technology for ISS scenario only. Refer to discussion in Section 6.2.3.
Anchor to the ISS	2	-	-	Core technology for ISS scenario only. Refer to discussion in Section 6.2.4.
Non-tethered: On-board energy generation	-	2	2	Core technology for exploration of Moon Lava tubes and low gravity bodies scenarios only. Refer to discussion in Section 6.2.5.
Environment protection	2	1	1	Refer to discussion in Section 6.2.6.
MOBILITY				
Path Planning	2	2	2	Refer to discussion in Section 6.3.1.
Locomotion Planning	1	1	1	Refer to discussion in Section 6.3.2.
Locomotion Types	1	1	1	Refer to discussion in Section 6.3.2.
Climbing	2	2	2	Refer to discussion in Section 6.3.3.

Next, we discuss further details of the core technologies that are designated Maturity Level 1 or 2.

6.1 Sensing and Perception - Core Technologies not yet Fully Mature

6.1.1 Proximity Detection

The ability to detect nearby objects/structures is particularly important onboard the ISS, where it is critical to avoid damaging equipment or disturbing crew. Several technologies exist that can be adopted for this purpose, including Camera-based (Time-Of-Flight, mono, stereo), ultrasound, Ultra Wide Band (UWB), Infrared Radiation (IR) and laser. The development of a good solution for the Proximity Detection functionality is viewed as rather challenging given the shape and size of the snake robot, but it is not expected to present any major implementation problems given the vast amount of research and development that is currently invested into the continued miniaturization of sensors.

6.1.2 Object Pose Estimation

3D object pose estimation is the ability to automatically determine the 3D position and orientation of an object (such as a handle). Pose estimation comprises both a sensing problem (which sensor(s) to choose) and a perception problem (how to best interpret the sensor data in order to do pose estimation).

Figure 15: A preliminary version of the Astrobee. Image: NASA.

Pose estimation of well-defined pre-known 3D objects based on camera images or high density / high accuracy 3D sensor data is to a large degree possible to do with technology today. Blank surfaces may constitute a main challenge in order to realize a generic system that can robustly estimate the pose of a wide variety of different objects. However, SINTEF and others are working on solutions for such a challenge. Moreover, in cases where the number of different objects are limited, then more customized solutions can be adapted and used.

As previously mentioned, a drone-like system called Astrobee is scheduled to be launched to the ISS at the end of 2017 [5]. The Astrobee comprise of cameras, LIDAR, cooling system, Central Processing Units (CPUs), batteries, docking system, communication system, fans, and pose estimation system. In particular, the Astrobee calculates pose estimates of ISS handrails based on 3D points clouds obtained from an onboard depth sensor. All these technologies are also relevant for snake robots onboard the ISS.

6.1.3 Robot Absolute Pose Estimate

Robot pose estimation concerns the ability of the snake robot to determine its position and orientation relative to its environment. It is advantageous that a robot's pose estimation system is solely on-board the robot. In other words, the system should not have to rely on customized external infrastructure such as radio beacons or markers. Such technology is available in the Astrobee where accelerometer, rategyro and camera data is used to determine its position [5]. The system is said to operate at about 6 Hz refresh rate.

In recent years, there has been much research and development on systems for Simultaneous Localization And Mapping (SLAM). Many results have been developed and published related to the full position/orientation estimation of micro aerial vehicles (including mapping-capability) where all computations are carried out onboard the vehicle. These results are highly relevant for both snake robots operating inside the ISS and within environments such as on asteroids or on the Moon.

6.1.4 Contact Sensing

Detecting contact between the snake robot and the environment, as well as estimating the size of the contact force along the full length of the snake robot are, important for at least two reasons:

1) To allow software algorithms to be used to reduce impact loads such that they are within acceptable limits (to be further discussed in Section 6.1.5).
2) To help characterize the properties of the surface that the snake robot is traversing.

To allow advanced locomotion planning for motion across some terrain, a key input is information about the characteristics of the environment the snake robot is attempting to traverse. The optimal locomotion strategy will be different depending on whether the surface is hard and slippery or soft and sticky. Hence, the snake robot should incorporate sensors that provide useful information about surface properties. Key sensors to accomplish this will be contact force sensors and accelerometers.

For snake robots, environment contact sensing systems have been developed by SINTEF and NTNU for several snake robots such as a snake robot prototype called Kulko [7] and Anna Konda [2]. These systems need to be integrated in the shell of the robot and required the robot shell to have a degree of compliance. This eventually led to some challenges. However, more recently a system for measuring the total forces and torques applied to each snake robot link was introduced with the snake robot called Mamba mentioned in Section 6.1.5 (see also Figure 16). This sensing system is integrated into the snake robot and does not need to be somewhere close to the surface of the robot. This makes it more robust against the various types of environments that the robot may encounter. Still, this system needs further development and testing before being able to operate robustly in space.

Figure 16: The "Mamba" snake robot developed by NTNU and SINTEF.

6.1.5 Inherently Safe Joint Movement

It is critical that the snake robot developed for use onboard the ISS is not able to harm the crew or the ISS infrastructure. High impact loads are a function of both the material stiffness of the robot as well as the effective inertia. While the effective inertia can be limited by use of software and sensor technology, unpredictable behaviour may still occur as a result of hardware or software faults. Thus, the mechanical characteristics of the robot must be considered in order to improve the overall safety. The almost ISS ready Astrobee, incorporates several such precautions into the physical design [5]. The perching arm is designed to be flexible and backdrivable with a grip not strong enough to cause any crew injuries. The Astrobee is also encased in an impact-absorbing foam shell which is designed to deform and absorb most of the impact energy in case of a collision at the worst-case velocity (to be further discussed in Section 6.2.3).

Robot joints can be designed to be flexible using both active and passive mechanisms. A variable stiffness actuator is a mechatronic device that is developed to build passive compliance robots [8]. However, such devices add significant complexity to both the design and control of robot joints. A snake robot called "Mamba" is designed such that all torques and forces acting on each joint can be measured [9]. These measurements can be used to implement flexibility as an active mechanism since the robot will be aware of any abnormal forces acting on the snake robot body. Flexibility is important both to reduce the potential harmful effect of pinch points, as well that a snake robot can change the shape of its body to reduce impact forces during collisions.

To prevent collisions through software algorithms, the snake robot must be acutely aware of the position of its (entire) body relative to the position of nearby objects. Several technologies exist that can be adopted for this purpose, including camera-based (Time-Of-Flight, mono, stereo), ultrasound, Ultra Wide Band (UWB), InfraRed (IR), laser and 3D depth sensors. To develop a good solution for the proximity detection functionality is viewed as somewhat challenging given the shape and size of the snake robot, difficulty of obtaining full sensor coverage and given that the robot may operate in very close vicinity or even in direct physical contact with the crew (e.g. if an astronaut launches a snake robot behind an equipment rack). Although mission performance requirements need to be further specified in order to fully understand whether it would be possible to build a snake robot which would be inherently safe to operate, the challenges identified so far represent good research challenges that are expected to be solved to a satisfactory level. As an example, robot manipulator systems such as the Kuka Iiwa[1] is developed to operate in collaboration with humans – i.e., so-called "collaborative robots". Iiwa has torque sensors integrated in each joint to detect unwanted contact with the environment and to be able to operate compliant if necessary.

6.2 Mechatronics – Core Technologies not yet Fully Mature

6.2.1 Joint Actuation

For snake robots without wheels or tracks, actuation of the joints is the only way for a snake robot to gain propulsion. It is most common for snake robots to have one motor-gear system per actuated degree of freedom, thus it will have two such systems per cardan joint, and only one system per one-degree-of-freedom joint. We provide information regarding some joint module parameters for the NTNU-SINTEF snake robot called Mamba – where each joint has a separate motor-gear system – in Figure 17.

Parameter	Value
Weight	310 g
Width/height	70 mm
Length between joint axes	89 mm
Degrees of freedom	1
Max joint travel	+/- 90 deg
Max continuous joint torque	2.3 Nm
Max joint speed (no load)	429 deg/s

Figure 17: Parameters for a joint module in the "Mamba" snake robot [9].

Other solutions have been proposed such as a snake robot called OmniTread [15] where the snake robot only has one motor, but a complex system of gears and connections in order to transfer the torque produced by the motor onto the snake robot's joints.

In low gravity environments, the main challenge is to identify suitable actuator-gear combinations that can achieve necessary joint speed and torque and at the same time fulfil any constraints on the size of the motor-gear system. Such constraints could require the snake robot to have a very small cross-sectional area to allow access to spaces behind or within infrastructure on the ISS.

Snake robots will benefit from being able to lift parts of their body to achieve locomotion in challenging environments such as rocky areas or areas with soft sand. For operations on the lunar surface a snake robot would need to be fitted with environment protection and heating. Hence, each snake robot link may become quite heavy. In order to lift one or more heavy links, a snake robot would need to have a strong and robust motor-gear system. However, as torque and robustness of a motor-gear system increases, such does also its weight usually. Thus, requiring even stronger motor-gear systems to lift the weight of the snake robot links.

[1] Kuka Iiwa: https://www.kuka.com/en-de/products/robot-systems/industrial-robots/lbr-iiwa

Based on the above discussion, the identification of (or possibly the development of) motor-gear systems for joint actuation of snake robots operating in the harsh space environment is viewed as one of the main challenges for realizing snake robots for planetary exploration.

6.2.2 High Friction Contact

It is important that the snake robot gripper is not so strong that it can damage the crew onboard the ISS. Hence, a high-friction material inside the gripper can ensure a sufficiently stable grip either around a tool or around the ISS handrails. New materials such as non-permanent ("dry") high-capacity reusable adhesives provides new possibilities. It may also be useful to consider use of such a high-friction material on key portions of the exterior skin of the snake robot to obtain the needed friction forces with the environment.

A candidate solution is adhesion inspired by that found on the Gecko toe-pads currently being extensively researched. In [10] the authors refer to previous results demonstrating reusable gecko-like adhesives on smooth surfaces such as glass with high shear force capacities (~300 kg for a 100 cm^2 adhesive) and which can be released with very little force (<1 kg in peel). They also claim to have demonstrated that gecko-like adhesives are able to adhere robustly to a wide range of "real world" surfaces. Some concerns still remain regarding the ability to make the skin stick to all relevant surfaces and then to be able to efficiently detach from it. Note that a Gecko robot ("Abigaille" crawling robot) has previously been tested by ESA and received good critics[2].

6.2.3 Collision Absorption

The snake robot concept for use onboard the ISS, requires each snake robot segment/module to be encased in an impact-absorbing foam shell to prevent the robot from damaging any ISS infrastructure or equipment or hurting any of the crewmembers in case a collision was to occur. The shell must be designed to deform and absorb most of the impact energy in case of a collision at the worst-case velocity. The main uncertainty related to this functionality is how the shell can be designed to cover all relevant portions of the snake robot without limiting the flexibility/mobility of the robot.

6.2.4 Anchor to the ISS

The snake robot concept for use onboard the ISS will have the ability to grab onto the ISS handrail using the gripper located at either end of the snake robot and have the ability to "perch" on the handrail in a similar fashion as the Astrobee. Like the Astrobee, the snake robot will rely on the onboard camera systems to detect the 3D shape of the handrails and determine the relative pose of the robot during the docking approach. As mentioned previously the "hand-over-hand" or "inchworm" method of locomotion illustrated in Figure 13 is relevant. This method of locomotion mimics that employed already by the "Canadarm2" to move around the outside of the ISS. Canadarm2 is a 17-meter-long robotic arm with 7 motorized joints [11]. The robotic arm is not permanently anchored at either end and is able to move around the outside of the station flipping end-over-end limited only by the number of Power Data Grapple Fixtures (PDGF). As the name indicates, each fixture provides the arm with power and a computer/video link to astronaut controllers inside. The arm can also travel the entire length of the space station using the Mobile Base System (MBS). All the experience gathered through years of use of the Canadarm2, will likely prove very helpful for the development of a similar, much-smaller scale system for use inside the space station. As is illustrated in the pictures from inside the ISS in Section 3.1, there are a number of handrails already installed, but detailed analysis should determine if it would be beneficial to install additional handrails for snake robot locomotion purposes.

6.2.5 Non-tethered: On-board Energy Generation/Supply

Previous Mars rovers have been looked to for inspiration for how to generate energy onboard the robot for scenarios where a lander/rover cannot be relied on to supply the power. Mars rovers Spirit and Opportunity

[2] http://m.esa.int/Our_Activities/Space_Engineering_Technology/Wall-crawling_gecko_robots_can_stick_in_space_too

used triplejunction solar arrays that would charge two lithium-ion batteries, as the main power supply. Mars rover Curiosity, which weighs about 900 kg (nearly 5 times heavier than Spirit and Opportunity), instead incorporated a Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) in order to generate constant power regardless of the availability of the sun. Both of these options could likely be adopted for the exploration of low-gravity body scenario, but for exploration of lunar lava tubes only MMRTG is a practical option for longer duration missions.

Another option for energy generation that has previously been successfully applied both during the Apollo missions and onboard the Spaceshuttle is fuel cells. While recent research has rendered the fuel cells increasingly efficient, it will in the best scenario last for a few weeks meaning poor energy to mass ratio compared to the alternatives. Also, the supporting systems (e.g. fuel tanks, and plumbing) adds a lot of complexity to the overall design. However, NASA is currently working on the development of regenerative fuel cell systems where solar arrays will power an electrolyser that separates water into hydrogen and oxygen and then use the hydrogen to produce electricity through a fuel cell. The waste water from the fuel cells can then be recycled, the process can repeat, thus enabling continuous energy production and usage. In effect the regenerative fuel cell system represents an energy storage capability claimed to exceed that of advanced batteries [12]. This technology can be adopted to cover all the energy generation needs by incorporating large solar panels, or to allow an emergency charging capability trough very small solar panels in order to avoid complete loss of a vehicle if it were to run out of fuel (in this case water).

The main uncertainty associated with all the above technologies, is the ability to size the power generation devices to the snake robot.

6.2.6 Environment Protection

It is essential to the success of the snake robot mission that the robot systems can survive the harsh environment it will be operating in. The specific requirements to environmental protection will vary significantly depending on whether the snake robot is designed for use onboard the ISS or for exploration of low gravity bodies. However, the key properties that need to be optimized on for a given snake robot concept includes structural protection (against puncture, rupture etc.) of delicate internal components and thermal control of the critical robot systems such that they are working within their allowable temperature range. In the remainder of this section, the discussion is focused on a snake robot concept for exploration of lunar lava tubes or for low-gravity bodies which will face a significantly more challenging environment than a snake robot concept for use onboard the ISS. The technologies used for the Mars rovers have been reviewed for inspiration into how robust environmental protection can be achieved.

First off, a robust shell is required in order to protect the internal components of the robot from impacting objects such as micrometeors and from more general wear and tear as the robot traverses challenging terrain. Extreme temperature changes is a major threat to the essential computer and electronics components onboard the robot, and these should be housed inside a protective box, which will likely be the same as the robust outer shell. On the Mars rovers, this box is referred to as Warm Electronics Box (WEB) or simply the "rover body". In order to trap heat inside the body walls a special layer of lightweight insulation made from a substance such as Solid Silica Aerogel (used on the Mars rovers) should be incorporated. To further minimize heat radiation from the robot, the robot body should be painted with a reflective coating. Mars rovers Spirit and Opportunity used a sputtered gold film.

For heating, the Mars rovers rely on electrical heaters that operate when necessary (using thermal switches) and Radioisotope Heater Units (RHUs) which are constant heaters the size of a C-cell battery that generate about 1-watt heat through the radioactive decay of a low-grade isotope. Curiosity incorporated a Heat Rejection System (HRS) consisting of pumps and a fluid loop to distribute heat between the different robot components as necessary, including excess heat from the MMRTG. This represented the first use of such a system on a rover or lander on the surface of a planet. It may also be relevant to provide means to allow heat to escape the WEB to prevent the electronics from overheating during daytime. The radiator is typically a conductive panel usually coated with a high-emissive coating. To deal with changing thermal conditions, some way of modifying the emissivity is ideal. Larger spacecraft typically install louvres on top of the radiator for this purpose.

Note that a tethered snake robot also requires thermal protection of the actual tether, which may lead to a fairly bulky design and effectively limit the range of the snake robot.

It is not likely that all the technology developed for the Mars rovers discussed above will be possible to implement onboard a quite differently shaped and most likely both smaller and lighter snake robot. In fact, thermal control is viewed as one of the last hurdles to developing miniature spacecraft. A promising technology emerging that is particularly relevant for micro (< 20 kg) spacecraft includes advanced thermal control coatings that can change their effective emissivity in response to a control signal. Several technologies are being developed, including electrochromic solutions, electrostatic solutions and micro-louvers. The electrochromic devices involve some chemical process to vary the emissivity of a surface. The electrostatic devices include a thin film where an electrically conductive coating has been applied on the inside while a white paint has been applied on the outside. The film can be electrostatically held off a radiative surface to act as a layer of insulation or can be held tight against the surface to radiate heat efficiently. The micro-louvers function similar to a traditional louver, by physically modifying the radiating surface, except that their scale is on the order of microns. A good example of such an advanced "thin skin", specifically a variable-emittance infrared electrochromic skin, is developed by Ashwin-Ushas Corporation in collaboration with NASA, and is presented in [13]. Additionally, the distributed fashion of the snake robot modules may require a pumped liquid cooling system to thermally couple all the modules. A concept for MEMS-based pumped liquid cooling system for future micro/nano spacecraft is presented in [14]. In summary, the recent advances and research focus on thermal control strategies for nano and micro spacecraft, renders adequate thermal control of a snake robot in space challenging but technically feasible.

6.3 Mobility – Core Technologies not yet Fully Mature

6.3.1 Path Planning

Path planning is required for the snake robot to (autonomously) make decisions on the optimal path selection between a point A and a point B. A wide range of strategies and algorithms for similar applications exist in both the fields of automatic vehicle control and robotics. The novelty involved with path planning for a snake robot is tied to the link between path planning and locomotion planning. For instance, is it better to climb over or crawl around an obstacle? By taking advantage of the flexible snake robot body, several locomotion strategies may be relevant for a particular path segment. The path planner should collaborate with the locomotion planner to ensure that some criteria on the optimal path between A and B are satisfied. An example implementation is to have the Path Planner (PP) send a short list of "most probable paths" (based on camera images and terrain information) to the Locomotion Planner (LP), the LP will then return the best locomotion selection for each path to the and PP, and finally the PP will perform the path optimization compared to desired mission criteria such as to minimize the power required.

6.3.2 Locomotion Planning / Locomotion Types

To properly take advantage of the flexibility offered by the snake robot design is key to the success of all snake robot concepts in space. Ideally each snake robot will have several options for motion towards a desired target, and the best choice will be a function of the terrain, the surface properties and mission details such as the time and energy available. Previous research has been performed on snake locomotion inspired by real snake motions as presented in section 2.4 of this document. A particular field of interest for locomotion on the Moon and on asteroids is obstacle aided locomotion – inspired by lateral undulation– where a snake robot would push against indentations on the ground to move forward [7].

Snake robot locomotion in a zero/low gravity environment has not yet been subject to research. Obstacle-aided locomotion and concertina locomotion are of interest for this latter scenario as a snake robot could push against its surroundings for locomotion. One may consider to add some caterpillar features for additional gripping capability inspired by the "inchworm method". The geometer moth caterpillar (or inchworm) is equipped with appendages at both ends of the body. It clasps with its front legs and draws up the hind end, then clasps with the hind end (prolegs) and reaches out for a new front attachment.

Special considerations for getting around the ISS have been discussed in Section 6.2.4.

6.3.3 Climbing

Most three-dimensional environment includes some major obstacles such as boulder fields, hills and sheer cliffs. Depending on the type of obstacle, a different climbing technique may be required for successful traversal. For instance, the ability to climb up tree trunks have been demonstrated where the snake robot wraps around and essentially rolls up the tree trunk [16]. However, of primary interest to operations in space environments is the ability to ascend a steep slope or to traverse a significant elevation "step-change" such as a sheer cliff.

The degree of difficulty involved with the transversal of a slope is mainly tied to the steepness and the friction and irregularities of the surface. In the presence of adequate friction and/or vertical affordances, several modes of locomotion may be possible. Particularly, the obstacle-aided locomotion where the snake robot would push against indentations on the ground to move forward [7] should be considered.

In case of a vertical wall/cliff or a slope that proves too steep or slippery for other types of locomotion, the snake robot would need to extend its body vertically mainly by means of its own joints. Such "rearing up" ability have been demonstrated by several, the Gen 2 snake robot developed by NASA Ames is shown in Figure 18.

In most real-life scenarios, it is expected that a combination of obstacle-aided locomotion and rearing-up manoeuvres will be required to ascend challenging terrain such as a steep boulder field.

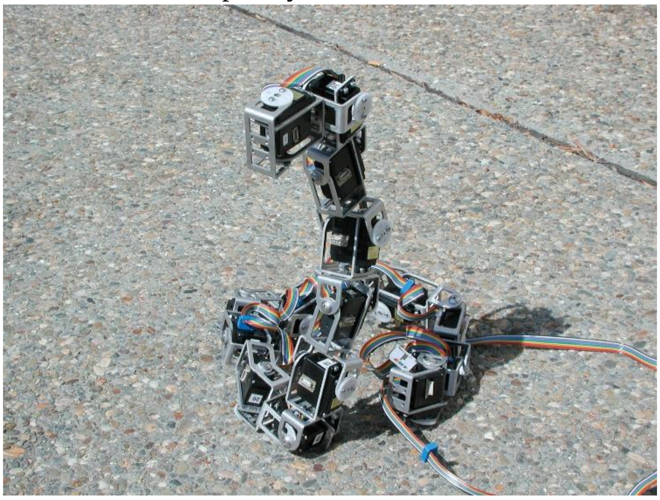

Figure 18: NASA Gen 2 Snake Robot Demonstrating Rearing Capabilities. Credit: NASA

7 Conclusions and Further Work

The report has identified and explored three promising scenarios in space where a snake robot design may be relevant. Snake robot concepts have been developed for inspection and intervention activities onboard the ISS, for exploration of lunar lava tubes and for exploration of low gravity bodies. The core technologies for each concept have been identified, these primarily relate to locomotion in challenging terrain, environmental protection, power supply and protection of ISS crew and equipment. While a successful snake robot design faces many challenges, emerging technologies aimed at micro spacecraft, renders these concepts feasible in the not too distant future.

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